DEVELOPMENT OF GUIDE FOR SELECTION OF SUBSTRUCTURE FOR ABC PROJECTS

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Note: Highlighted sections are under development by Oklahoma University

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1 Introduction

Accelerated Bridge Construction (ABC) is a construction type that reduces the onsite construction time mainly using prefabricated bridge elements and systems (PBES) constructed offsite. To achieve the ABC mission, new and innovative materials, design, and construction methods are implemented in designing and construction of new bridges as well as in the replacement and rehabilitation of existing bridges. For prefabricated elements, the construction of bridge components is in a high control environment which leads to improving the quality, safety, and durability of bridge elements. Also, prefabrication avoids typically weather-related delays and also have no or little impact on traffic flow in comparing with conventional construction methods.

While much attention has been paid to means and methods of accelerated construction of the bridge superstructure, little has been done to provide proper guidance to designers and bridge owners on the selection of type, design and construction of the substructure and foundation. For this purpose, a research study was initiated at the Accelerated Bridge Construction University Transportation Center (ABC-UTC) to develop guidelines that can be readily used by practitioners for the selection of substructures and foundations for different accelerated bridge construction (ABC) projects. The primary objective was to assist in decision making process for the selection of substructure and foundation for new bridges and replacement of existing bridges using the ABC methods, including evaluation, retrofitting, design, and construction. To accommodate this, it was necessary to review current practice, available construction methods, prefabricated elements and systems, factors influencing the selection process, and to develop tools to facilitate decision making including tables, flowcharts, and life-cycle cost analysis. Efforts was divided into two major categories: new bridge construction and existing bridge replacement. An attempt was also made to identify issues and obstacles preventing the adoption of ABC substructures and foundations for bridge projects, and exploring solutions for facilitating a wider use of ABC substructure. Development of the Guidelines relied on information from various sources including open literature, survey of experts and stakeholders, input of ABC-UTC Advisory Board members, and other domain experts nationally and globally. Information obtained from these sources were reviewed, analyzed, and synthesized carefully and organized systematically. This research project is a collaborative project between Florida International University and the Oklahoma University. FIU focused its work on substructure and lead the development of the guideline, and OU focused its activities on foundation related subjects and provide support to FIU on other tasks.

1.1 Background

The aim of accelerated bridge construction (ABC) is to reduce the impact of bridge construction on the public and bridge usage by reducing the construction time, especially when replacement of an existing bridge is involved. In addition to reducing construction time significantly, ABC has been found to enhance safety and reduce congestion. Although much work has been done in the past to investigate the design, configuration, and erection methods for bridge superstructure, very limited studies have addressed substructures and foundations. For the purpose of this paper, “substructure” refers to all bridge elements supporting the superstructure and transferring the load to the foundation, i.e., everything below superstructure bearings and above foundation. “Foundation” refers to elements connecting the structure to ground and transferring loads (normally below ground).

Often, it is assumed that the bridge substructure and foundation are ready to receive the superstructure. Based on field experience, site-specific testing, design and construction of foundations and substructures can be the most time-consuming part of bridge construction. An informed and educated decision on the type of foundation and substructure may define the viability and economic feasibility of the entire ABC project. In the current study, the research team sought to develop guidelines for the selection of substructures and foundations for different ABC projects. The Guidelines include review of factors influencing design and construction of substructure and foundation including type, geometry, location, superstructure and bridge configurations, design methodology, accessibility and space availability, cost and risks, life-cycle performance, and compatibility between sub- and super-structure as well as between substructure and foundation. Questions related to construction of new bridges and replacement of existing bridges was addressed through development of procedures and flowcharts, including evaluation and strengthening of existing substructure and foundation for potential reuse.

The primary objective of this project therefore was to provide guidelines for decision making by the designers and bridge owners for the selection of substructure and foundation for new bridges and replacement of existing bridges using the ABC methods, including evaluation, retrofitting, design, and construction. The decision depends strongly on the type and configuration of the superstructure intended for the bridge and the construction methods to accommodate them. From compatibility and conformity considerations, the decision on the type and design of both substructure and superstructure needs to be done concurrently. Geometric parameters such as span length, bridge width and bridge clearance are also important parameters in the selection of substructure type. Hence, the study had to cover not only the substructure and foundation, but also superstructure and construction methods. The evaluation of substructure and foundation of existing bridges for their structural capacity and functional adequacy and decision on reuse or replacement is also an important part of this study.

The project team presented much of the information in the form of decision trees or flowcharts that links the selection decisions to input parameters and assessment tools.

1.2 Intended Users

This guideline will be of interest to highway officials, bridge construction, safety, design, inspection, maintenance and research engineers. This guideline is directly applicable to the selection, design, and construction of ABC projects, including new bridges and replacement of existing bridges. In particular, designers, bridge owners, and other stakeholders are able to use this guideline to determine the substructure and foundation that best serves their purposes.

1.3 Guideline Organization

The guideline is organized having in mind the flow of information and various level of familiarity with the subject among the readers. The chapters are organized in the following format;

Chapter 1- This chapter is to introduce the subject, to provide a snapshot of the material to be expected by the readers, to describe briefly the content of each chapter, and to provide a step-by-step procedure for facilitating the substructure and foundation selection process.

Chapter 2- This chapter covers definitions and descriptions for ABC bridges in general and introduces prefabricated bridge elements and systems available for ABC bridge construction. In addition to substructure and foundation, for completeness and demonstrating the interrelation among various bridge segment, superstructure elements and systems and construction methods are also discussed. Selection of substructure elements for new bridges is discussed on Chapter 3 and for replacement of existing bridges is included in Chapter 4.

Chapter 3- This chapter contains information and flowcharts for selection of substructure and foundation elements and systems for construction of a new bridge. Many aspects of substructure and foundation selection are dependent on the type of superstructure and construction method. Hence, this chapter begins with identifying the parameters for deciding to use ABC instead of conventional method, and those influencing the selection of construction methods and bridge elements and systems. Available procedure, flowcharts and guidance are provided first to assist the user in selection of construction methods and the corresponding superstructure elements and systems. The chapter then describes additional parameters that would influence substructure and foundation selection such as compatibility issues, water/soil/salt exposure, and vessel and debris impact. It also includes some considerations in the selection process including those related to design, geometry, cost, safety, etc. Flowcharts are also provided to help the selection process taking into account some of the major parameters and considerations identified in this study. These include flowcharts for;

- Selection of substructure for new bridges according to the superstructure design and geometry that in turn is determined by the type of construction method selected earlier.

- Selection of substructure based on the type of foundation.

- Selection of foundation for new bridges based on water level, soil resistance and design loads.

- Selection of foundation based on the type of soil.

After selecting the substructure elements for new bridges using these flowcharts, the reader can then go to Chapter 2 to obtain more detailed information on the selected elements.

Chapter 4- Replacement of the existing bridges with consideration of substructure and foundation reuse is discussed in this chapter. Durability and integrity evaluation methods for condition assessment, and structural analysis and capacity estimation for the existing substructure and foundation is outlines. Suitability of substructure to receive the superstructure is discussed based on design compatibility, capacity adequacy, and geometric compatibility. Decision making for reuse or replacement of substructure and foundation is then discussed. Bridge life-cycle-cost-analysis is introduced as a practical and necessary tool to help in decision making by offering various strategies, accounting for all costs, and identifying the preferred strategy. Finally, methods of geometric modification, strengthening and repair/rehabilitation are described that can be utilized for reuse of the substructures and foundations as an alternative to replacement. Several flowcharts are provided to summarize the decision-making process including;

- Flowchart for the process of suitability check for substructure to receive the superstructure.
- Available flowchart from FHWA substructure reuse.
- Newly developed extensive flowchart for decision making on reuse, strengthening, modification, or replacement of substructure and foundation in projects dealing with replacement of existing bridges.

After selecting the substructure and foundation elements for replacement bridges using these flowcharts, the reader can then go to Chapter 2 to obtain more detailed information on the selected elements.

Chapter 5- This chapter summarizes the results of a survey conducted among state DOTs in relation with their experience with substructure and foundation selection for ABC projects.

Chapter 6- Available design and construction guidelines for substructure and foundation are reviewed in this chapter.

Chapter 7- This chapter describes some of the new concepts for improving existing substructure elements, including utilization of new materials and systems.

1.4 How to Use the Guideline

This report brings together a collection of vast information in general on ABC methods, available prefabricated elements and systems, decision making for construction of new bridges and repair/rehabilitation or replacement of existing bridges. It focuses however on information and selection process for bridge substructure and foundation.

- Users who would like to review ABC construction methods and available prefabricated bridge elements and systems for substructure and foundation will go through Chapter 2.
- <u>For construction of new bridges</u>, the users will go to Chapter 3 to review the factors influencing the selection process and use the flowcharts that guide them step-by-step to selection of the appropriate elements and systems. The chapter provides some available processes and flowcharts for decision making on the use of ABC in first place, and the construction methods and superstructure type borrowed from

other literature. New procedures and flowcharts are however developed for selection of substructure and foundation types and elements. These flowcharts include;

- Flowchart in Figures 3-10a, 3-10b, 3-10c, and 3-10d for selection of type of substructure and its elements/systems for construction of new bridges.
- Flowchart in Figure 3-11 for selection of substructure and its elements/systems in regards with the type of foundation.
- Flowchart in Figure ?? (OU) for selection of foundation.
- Flowchart in Figure ?? OU for selection of foundation with respect to type of soil.

After selecting the substructure elements for new bridges using these flowcharts, the reader can then go to Chapter 2 to obtain more detailed information on the selected elements.

- For replacement or repair/rehabilitation of existing bridges, users will go to Chapter 4 to learn about evaluation methods for existing substructure and foundations, condition assessment and capacity estimation, and life-cycle cost analysis for defining and decision making on strategies involving reuse, repair, modification, or strengthening of substructure and foundations.
    - Flowchart in Figure 4-8 will help the users to check for suitability regarding geometric compatibility, adequacy of capacity, and design and detailing match when considering the reuse of substructure.
    - Flowchart in Figure 4-10 contains all steps necessary for evaluation, condition assessment, and capacity calculation of substructure and foundation, and decision making on reuse, modification, retrofitting or replacement of substructure and foundation.

After selecting the substructure and foundation elements for replacement bridges using these flowcharts, the reader can then go to Chapter 2 to obtain more detailed information on the selected elements.

- To review design and construction guidelines available for substructure and foundation, users will review Chapter 6.
- To review new development in relation with substructure and foundation, users will read Chapter 7.

2 ABC – Definitions and descriptions

Accelerated Bridge Construction (ABC) is a construction type that reduces onsite construction time. To achieve the ABC mission, new and innovative materials, design, and construction methods are implemented in designing and constructing new bridges as well as in the replacement and rehabilitation of existing bridges. To reduce the onsite construction time, prefabricated bridge elements and systems (PBES) are constructed offsite. For prefabricated elements, the construction of bridge components is in a highly controlled environment which leads to improving the quality, safety, and durability of bridge elements. Also, prefabrication avoids typically weather-related delays and also have none or little impact on traffic flow compared with conventional construction methods. The most prominent advantage of the ABC method is reducing construction effect on the traffic flow and traffic interruptions.

2.1 ABC Bridge Components

ABC bridge components, in general, includes superstructure, substructure, and foundation subsystems (Figure 2-1). The superstructure refers to deck and girders and everything above the deck [1]. The substructure refers to elements that hold the superstructure like piers, abutments, and wing walls, basically, everything below the superstructure bearing and above the foundation. Foundation is a part of substructure that transfers loads from the bridge to the earth and strata. It can be shallow or deep, and include footings, pile caps, piles, etc. The ABC bridge elements and components are connected to each other using joints and connections which normally are established in-situ [2, 3] (Figure 2-2). It should be noted that an alternative definition exists referring to everything below deck bearing as substructure including the foundation. However, this report subscribes to a definition of substructure that includes bridge components below the deck bearing and above the foundation. This definition helps to distinguish better the role of substructure and foundation as well as a better explanation for the scope of work by parties performing the project.

2.1.1 Superstructure

The superstructure refers to all the parts that are above the bridge bearing and provide the horizontal span. These elements carry loads from the deck span and provide the riding surface [4]. Superstructure includes girder and deck slab, miscellaneous elements, barriers, and railing. In summary, the ABC bridges superstructure components are listed in Table 2-1.

Table 2-1: Different ABC bridge superstructure elements

Element	Type	Comment
Precast Concrete Deck	Full-depth Precast Decks	Panels can be installed on steel or concrete girders
	Partial-depth Precast Deck	Panels can be installed on steel or concrete girders also to act as stay-in-place forms as well as part of the deck. Upper part of deck still needs to be cast-in-place
Cast-in-place Concrete Deck	Normally with Stay-in-place metal forms	Forms are supported by girders and facilitate casting without the need for scaffolding, therefore accelerating the construction
Other Deck Panel Types	FRP, Steel Grid, Exodermic, and Timber	Normally used for reducing dead weight for deck replacement projects.
Superstructure girders	Steel girders	Steel girders can have different shapes Main advantages is light weight
	Precast concrete girders	Different shapes of precast concrete girders includes I beam, U beam, Single and Double-tee beam, rectangular beam, voided slab beam, and box-shape beam

2.1.1.1 Deck Panels

The deck elements include roadway lanes, walkway, and sideways. The conventional method in the construction of deck panels involves cast-in-place concrete and normally uses stay-in-place deck forming to allow the curing and forming of the wet concrete. This method can provide a smooth riding surface. However, this type of bridge deck construction is one of the time-consuming construction activities. Therefore, the prefabrication of deck elements has a significant impact on reducing the overall bridge construction time. The prefabricated deck panel systems inlcude full-depth precast concrete deck, partial-depth precast concrete deck, open grid deck, concrete/steel hybrid deck, fiber reinforced polymer (FRP) deck, and timber deck panel. Table 2-2 summarizes different prefabricated deck systems and their installation times according to the Florida Department of Transportation [5].

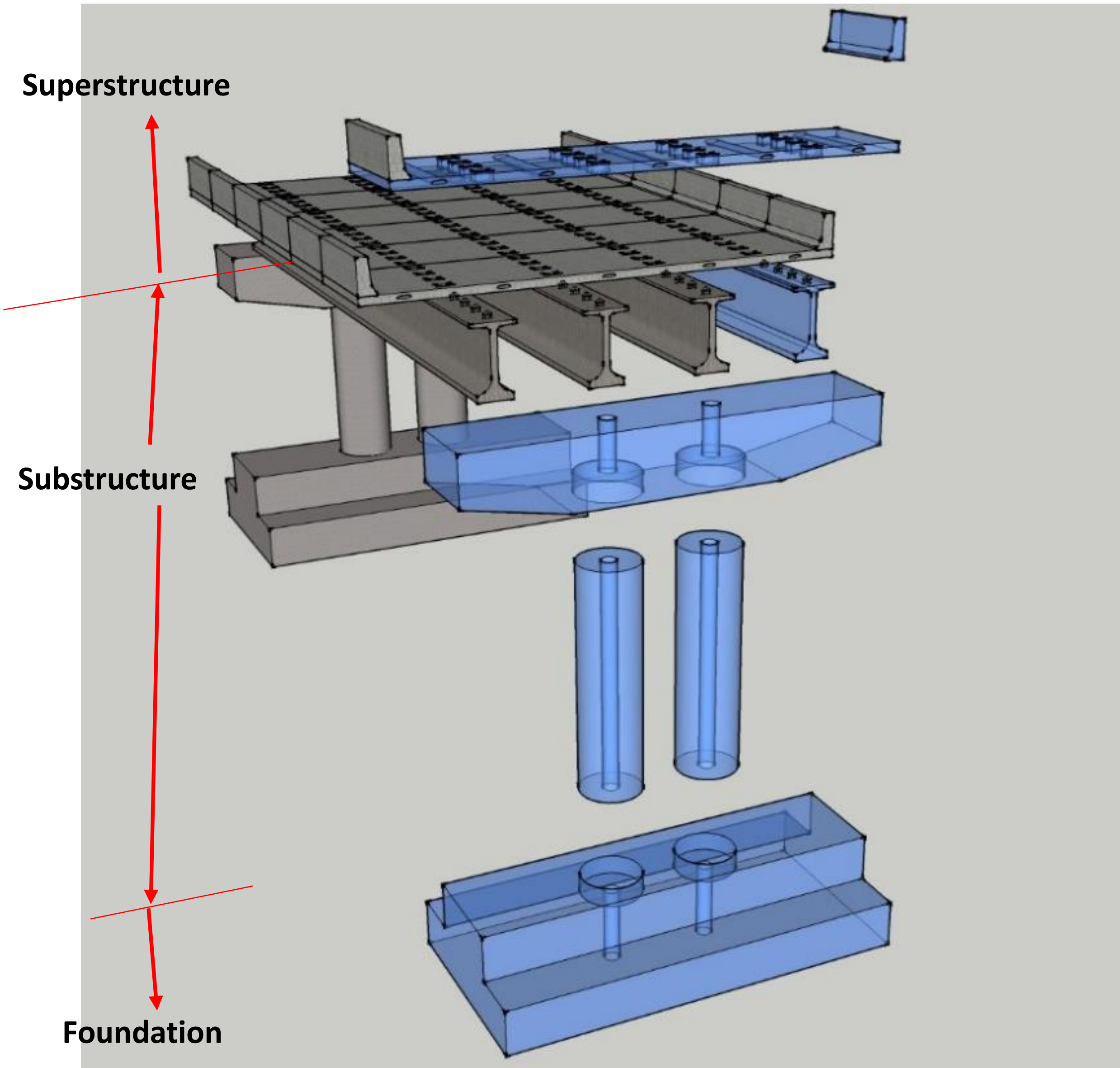


Figure 2-1: ABC bridge components

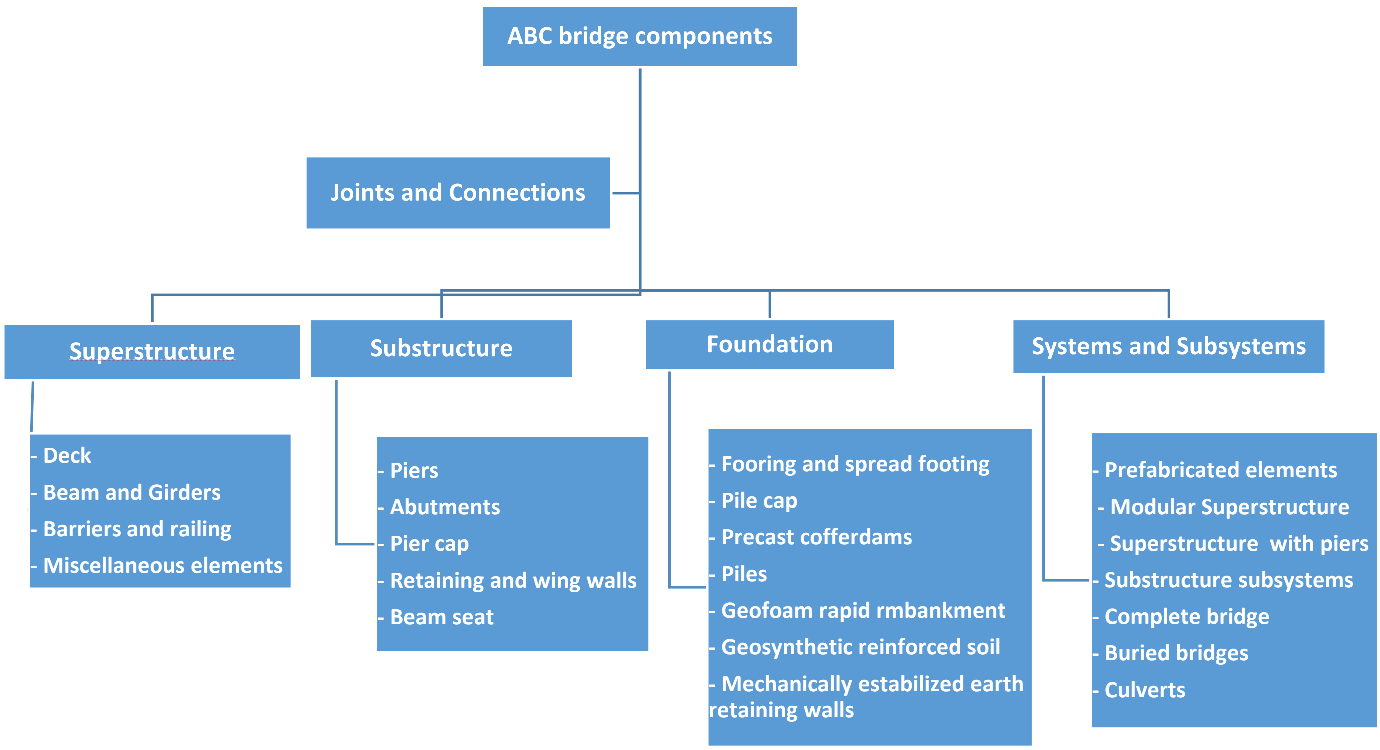


Figure 2-2: ABC bridge elements

Table 2-2: Prefabricated Deck panel systems [5]

Deck panel system	Installation time (days/span)
Full-depth precast concrete deck panel	2
Partial-depth precast concrete deck panel	7
Open grid deck panel	1
Concrete/steel hybrid deck panel	2
FRP deck panel	2
Timber deck panel	1

In full-depth precast deck panel application, the construction time of the bridge reduces more significantly than the partial-deck or stay-in-place forms (Figure 2-3) [1]. In this case, however, the shipping of panels may become an issue. To address potential transportation issues, the panels may be constructed near the bridge site. In full-depth deck construction, restressing or post-tensioning may be used. The deck panels are designed as one-way slabs, and longitudinal post-tensioned bars are used to integrate the slabs. Also, to attach the beam to the deck panel, blockout connections are used. Application of blockouts is critical for establishing composite action between slab and girders [1].

Partial-depth precast concrete panels, as also called "concrete framework," are 3.5 to 4-inches thick. The partial-depth deck forms the bottom of the deck. After placement of the partial deck panels on the top of the beams, a layer of concrete is cast on top of the panels to make the full depth of the deck [6].

Other alternatives to the full and partial-depth deck panel systems are open grid panels, fiber reinforced polymer (FRP) panel, timber deck, and steel/concrete hybrid deck panel systems. These systems are lightweight and can facilitate the shipping of the panels and are appropriate for moveable bridges. In open grid decks, the grid is filled partially with concrete (Figure 2-4). However, there is a concern about the durability of this system [5]. In timber deck systems, the glue-laminated deck panels are bolted or post-tensioned to connect to each other and provide the deck span (Figure 2-5). The design of these deck systems is described in AASHTO LRFD structural specification [7].

The two types of hybrid decks are partially filled grid decks and exodermic decks. In the partially filled grid, the upper portion of the steel grid within its depth is filled with concrete (Figure 2-6). The exodermic decks are similar to steel grid, but the concrete is placed mostly above the grid. The connection of the exodermic deck to girders is the same as the connection of a full-depth precast concrete deck. For example, for steel girders, pockets in the deck containing shear connectors welded to the top flange, are filled with grout. Another type of deck panels, called FRP, can be constructed from different type of fibers (Figure 2-7) and resins. Use of FRP in deck panel construction is preferable due to its lightweight, high strength, and high corrosion resistance [5].

The use of stay-in-place deck forms as metal sheets or concrete slabs can also be considered a method of accelerating the construction of the deck.

Figure 2-3: Prefabricated deck panel [1]

Figure 2-4: Open grid deck panel [1]

Figure 2-5: Timber deck panels [5]

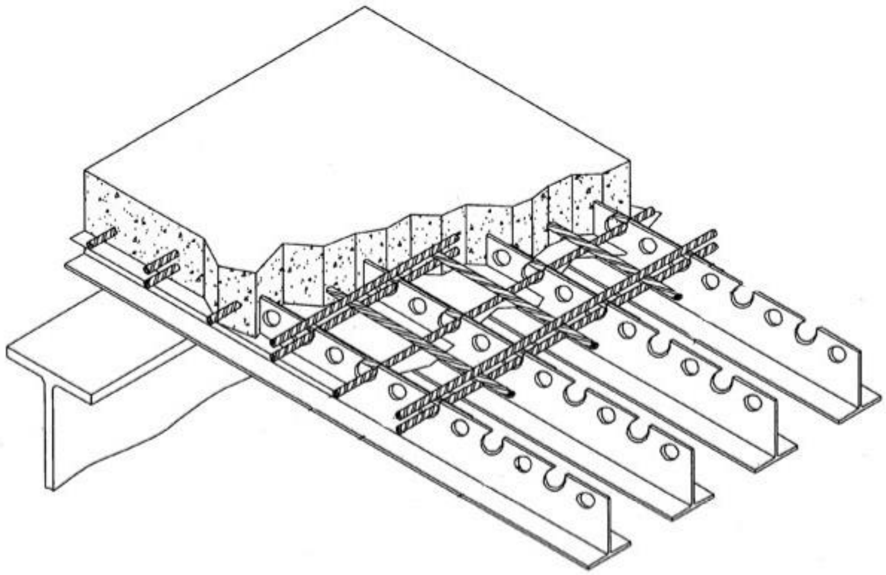


Figure 2-6: Exodermic deck panel [5]

Figure 2-7: FRP deck panel [5]

2.1.1.2 Girders

The girders are an essential part of bridge construction and include elements that bear the slab loads and transfer them to the substructure and foundation. The term girder sometimes is used interchangeably with beam in bridge construction and design. Girders can be constructed from steel or concrete.

Steel Girders

Steel girders can be configured in different shapes (Figure 2-8). The main advantage of using steel girders is their lightweight that can make shipping of prefabricated steel girders easier. However, the long-term maintenance and corrosion of steel girders are an issue. This issue, however, can be addressed by introducing weathering steel girders that require no painting and therefore less maintenance [1]. Also, it is possible to use steel beam with pre-topped concrete slab for replacement and construction of superstructure, which is called modular superstructure.

Precast Concrete Beam

Another type of girders is precast prestressed concrete beam. The AASHTO and precast/prestressed concrete institute (PCI) developed the standardized prefabricated girder shapes [8]. Different types of precasst concrete girders include I beam, U beam, Single and Double-tee beam, rectangular beam, voided slab beam, and box shape beam (Figure 2-9). Bulb-tee girders and decked-girders are two of the most efficient types of girders for ABC construction because they can eliminate the need for deck placement and decrease the bridge construction time.

Figure 2-8: Steel girder [9]

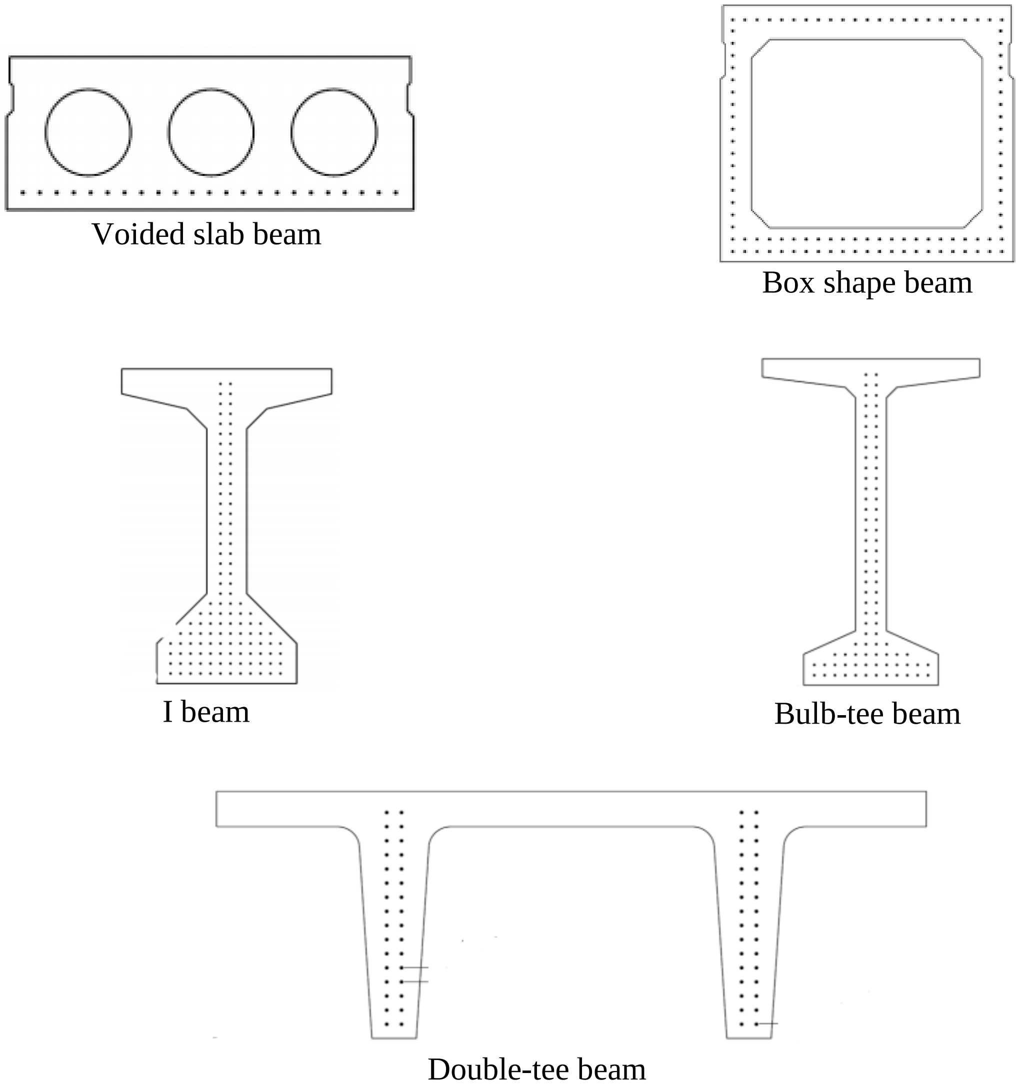


Figure 2-9: Different shape of precast girders [8]

2.1.1.3 Barriers and railing

The barriers for ABC bridges can be designed and constructed with prefabricated deck, cast in place, or attached to the deck using fasteners such as bolts (Figure 2-10). The FHWA provided a manual that defines the barrier and railing requirements for bridges [10]. This manual requires crash testing for barriers. To this date, no crash tested prefabricated barriers are available [1]. A prefabricated railing system has been developed recently by Iowa State University researchers as part of ABC-UTC projects that are verified with static/push-over testing. Next phase of this research project, aims at verification through crash testing of the proposed prefabricated railing system (Figure 2-11) [11].

Figure 2-10: Deck panel with a barrier [1]

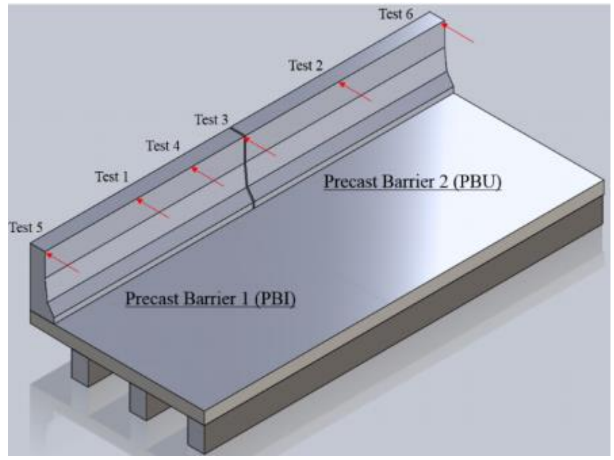


Figure 2-11: Deck panel with barrier [11]

2.1.1.4 Miscellaneous elements

Miscellaneous elements of the superstructure include the drainage assembly, lighting, expansion joints, bridge bearing, and deck overlay or riding surface of the bridge. The deck overlay or wearing surface can be surface of the bridge without any overlay or can be overlaid with asphaltmixes. The drainage assembly can be preinstalled on the prefabricated deck elements or established the same way as conventional bridges [12].

In conventional cast-in-place bridge deck construction, elevation adjustments to deck is performed by the use of deck hunches between top of the girder and bottom of the deck. In ABC projects with prefabricated girders and deck, bridge bearing is placed between girder and cap beam to provide bearing and adjust the elevation of girder and deck to provide proper, durable and uniform seating for the girders (Figure 2-12) [1].

The deck expansion joints are necessary for accommodating changes due to temperature variation and preventing premature deterioration or overloading of the bridge [13]. Expansion joints are not used for the case of integral abutments that become monolithic with the superstructure [1]. Expansion joints can be categorized into two groups [1]. The first group includes joints within the deck overlay and consists of asphaltic plug material and epoxy header with glands or seals. The second group includes joints embedded into the deck. The embedded joints experience large movements. Different types of embedded joints include modular expansion joints, armored seals, or finger joints. The issue with expansion joints is that they can deteriorate rapidly and need high maintenance. To address this issue, link slab has been introduced to eliminate the use of expansion joints in ABC projects [14]. Practical recommendation and guideline to use link slab in the ABC projects is under development and will be available shortly.

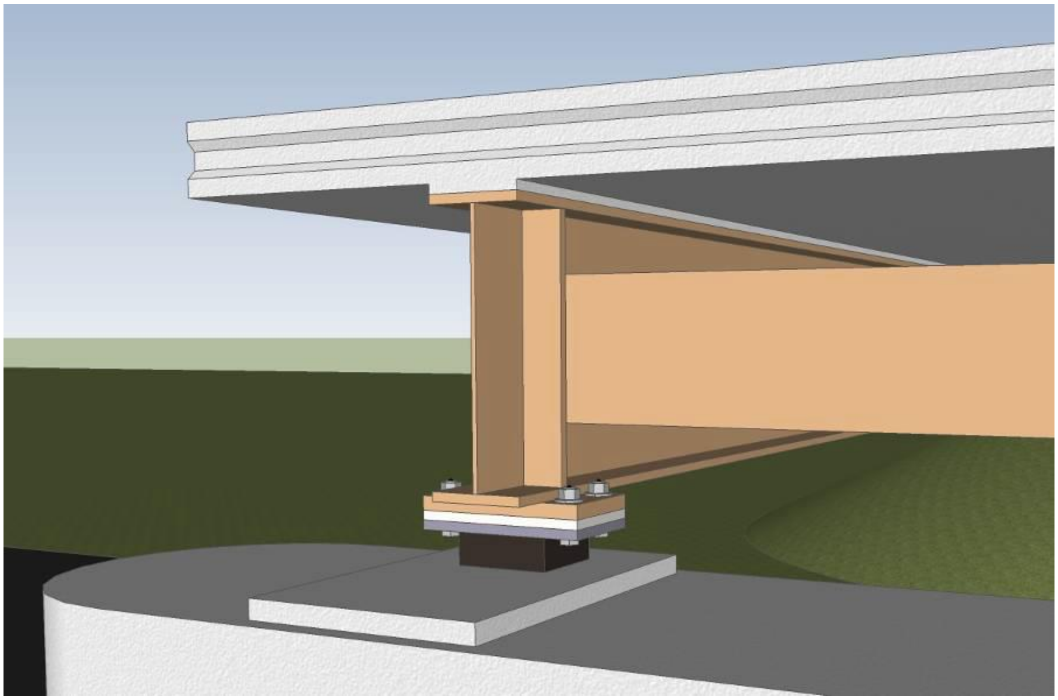


Figure 2-12: Bridge bearing [1]

2.1.2 Substructure

Substructure elements transfer vertical and horizontal loads from superstructure to the foundation. Piers, pier cap, abutments, culvert, wing walls, and retaining walls are the substructure elements (Figure 2-13) [1]. Different substructure elements are summarized in Table 2-3.

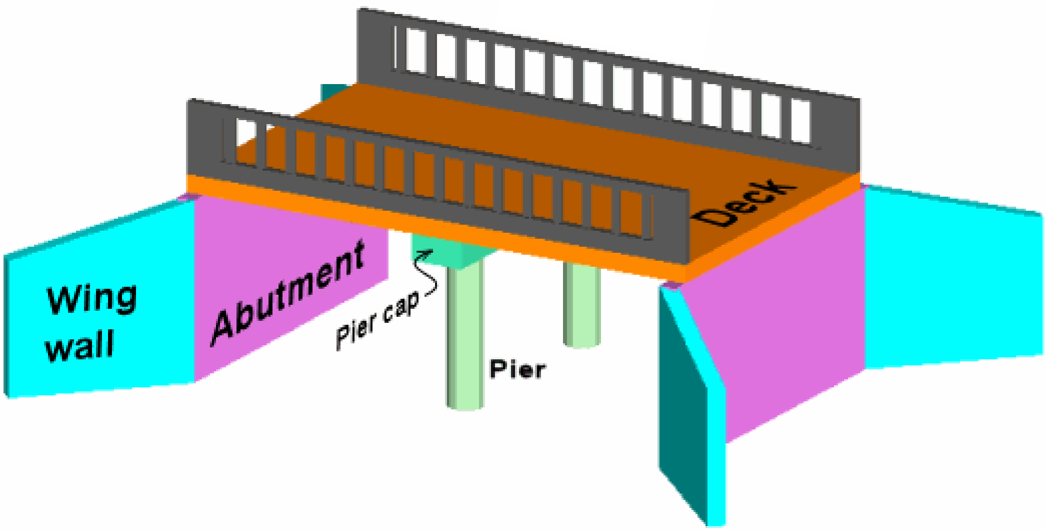


Figure 2-13: Substructure elements

Table 2-3: Different ABC bridge substructure elements

Element	Type	Comment
Substructure Piers or columns	Piers and pier bents	Vertical elements that support deck span Piers that consist of more than one column are called pier bent
	Wall piers	Used when the pier is affected by the errant vehicles Used in rivers to prevent debris from collecting between columns
Abutments	Fully integral abutment	Abutment is constructed with superstructure Abutment connection to the superstructure is a full moment connection
	Semi-integral abutment which	A portion of the abutment is constructed with the superstructure, Abutment connection to the superstructure is a pin connection
	Cantilever/stub abutment	Constructed separately from superstructure
	Spill-through abutment	Constructed separately from superstructure It is a cantilever abutment with a large void in its stem
	Retaining wall and wing wall	Abutment extension to retain embankment soil pressure in the approach embankment
Pier cap	Rectangular pier cap	Used when there is a precast girder or steel girder that can sit directly on top of the pier cap
	Inverted-tee pier cap	Used to provide better under clearance below the cap
Culverts	Three-sided culvert	Have a rectangular cross-section with varying wall thickness.
	Box culvert	Has a rectangular cross-section
	Arched culvert	The precast strips are placed side by side to create the bridge span The arch culverts can be slid under the existing bridge without closing the bridge

2.1.2.1 Piers

Piers are vertical elements that support deck span at intermediate points and typically consist of pier columns and pier caps. This element transfers loads to the foundation and resists horizontal loads using its shear resistance mechanism. Piers consisting of more than one columns are called pier bent (Figure 2-14) [1]. To connect pier cap and column, various types of connections are used. One type of connection is grouted splice reinforcing bar couplers. When the pier is affected by errant vehicles or is adjacent to a railroad, a wall pier may be used instead of pier (Figure 2-15) [1]. The integrity of piers connection to the pier cap and footing is essential, especially in the seismic region because they should resist the majority of shear and seismic loads.

Piers can be of steel or reinforced concrete. Concrete-filled tubes (CFTs) is a composite steel-tube filled with concrete that can be used as pier column. Several studies conducted on CFTs showed they are suitable for ABC projects due to their rapid construction and high strength to size efficiency [15]. Also, there is an ongoing study under the ABC-UTC program to identify connection types between CFT and pier cap or footing, and to investigate their ductility, capacity, and overall structural behavior [16].

Figure 2-14: Prefabricated pier bent [1]

Figure 2-15: Wall Pier [1]

2.1.2.2 Abutments

Abutments are elements that sustain the live and dead load of superstructure, retain the earth or lateral pressure from embankment, and resist sliding and overturning due to the embankment. Abutments consist of walls, wing-walls, and abutment caps. In fact, abutments play both pier and retaining wall function. Abutments are constructed at the beginning and the end of the bridge span where the superstructure rests on land [1]. Although the abutments can be constructed integrally or semi-integrally with the superstructure or built as a conventional free-standing abutment, integral or semi-integral construction of abutment is more popular.

Construction of abutments integrally with the superstructure has two significant advantages compared to the conventional free-standing abutment construction. Integral and semi-integral abutments have no deck joints and transfer embankment soil force to the superstructure and vice versa [1]. In the fully integral abutment, the abutment connection to the superstructure is a full moment connection. However, in semi-integral abutment where a portion of the abutment is constructed with the superstructure, a pin connection is used to allow rotation of superstructure in respect to the substructure (Figure 2-16) [1]. For the cases that the abutment cap can be directly connected to the end of piles, as shown in Figure 2-17, integrity between the piles and abutment cap can be established with the use of special socket or pocket connection. In this construction type, the abutment is supported on a row of piles normally designed to accommodate the thermal movement of the structure. This abutment configuration was constructed based on the specification for integral abutments used by the Utah DOT as well as by several other states DOTs. The corrugated void connection was used in this abutment. To create the voids in the abutment stem, corrugated steel pipe was used. Recently, a research project as a part of ABC-UTC project has been introduced to investigate the constructability of abutment details and evaluate the strength and durability of abutment connections [17]. This project is expected to facilitate the use of abutments in the ABC project by providing a detailed document for the construction of abutments.

Other types of prefabricated abutments are cantilever and spill-through abutments (Figure 2-18). These abutments are constructed separately from superstructure and retain the soil pressure and superstructure loads. In the cantilever abutment, wall stem connects to the footing using different connections like grouted splice couplers. To attach the wall to the abutment cap, the reinforcing bar cage which is cast into the corrugated voids can be used [1]. The corrugated steel pipes can be used to create the voids and to reduce weight of the abutment elements. When a large void is erected in the cantilever stem, it is called spill-through abutment. The erection of this void can reduce the soil pressure on the abutment significantly.

The retaining wall and wing wall are the abutment extension to maintain the earth pressure in the approach embankment (Figure 2-19). These walls are constructed at the abutment and are designed to resist earth pressure from backfill, surcharge from the live load, and hydrostatic load from saturated soil. If these walls are not constructed, the earth stays in its natural configuration [1].

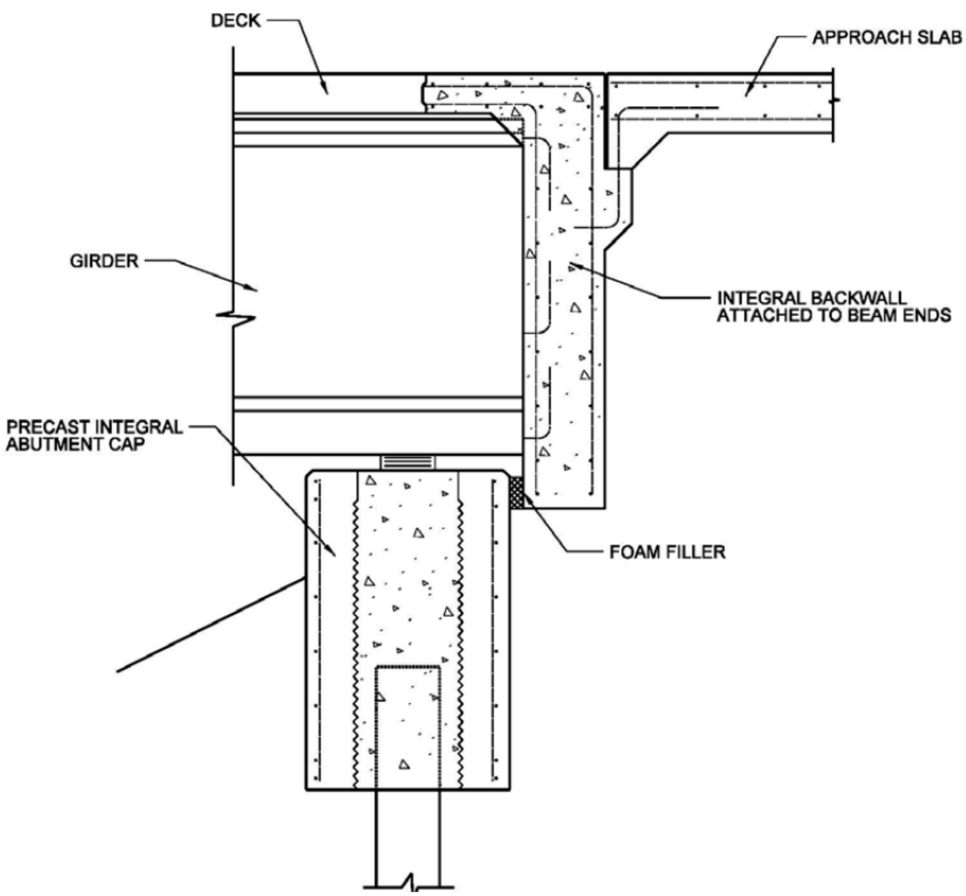


Figure 2-16: Semi-integral abutment [1]

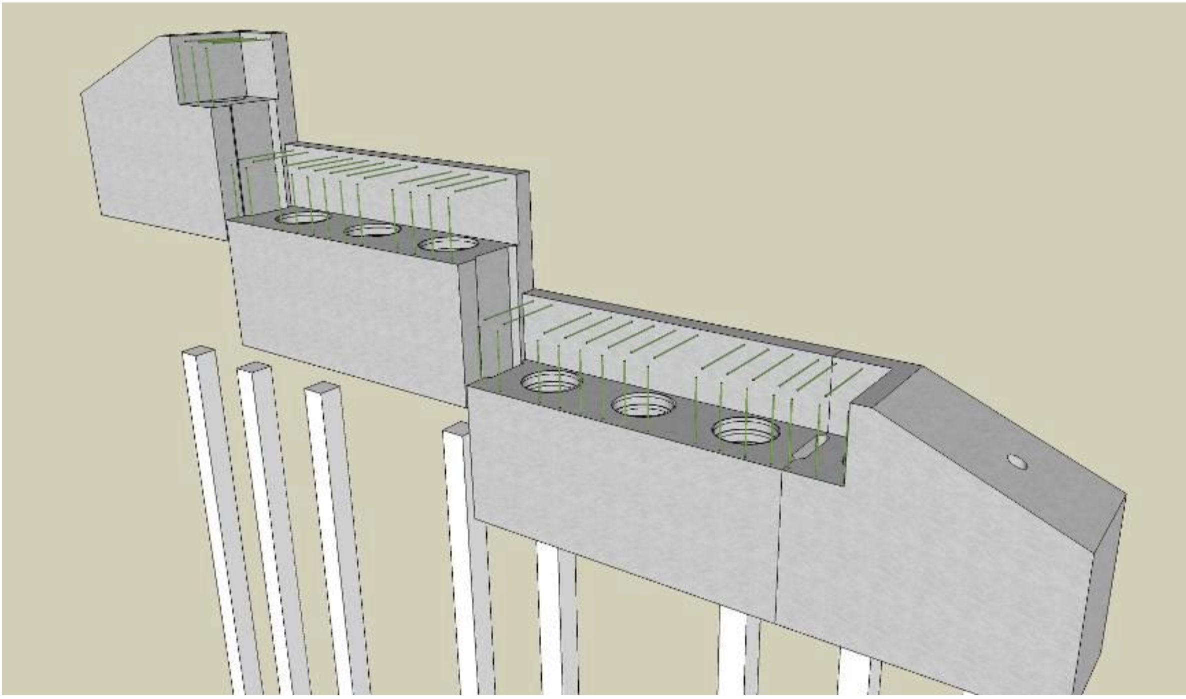


Figure 2-17: Prefabricated integral abutment [1]

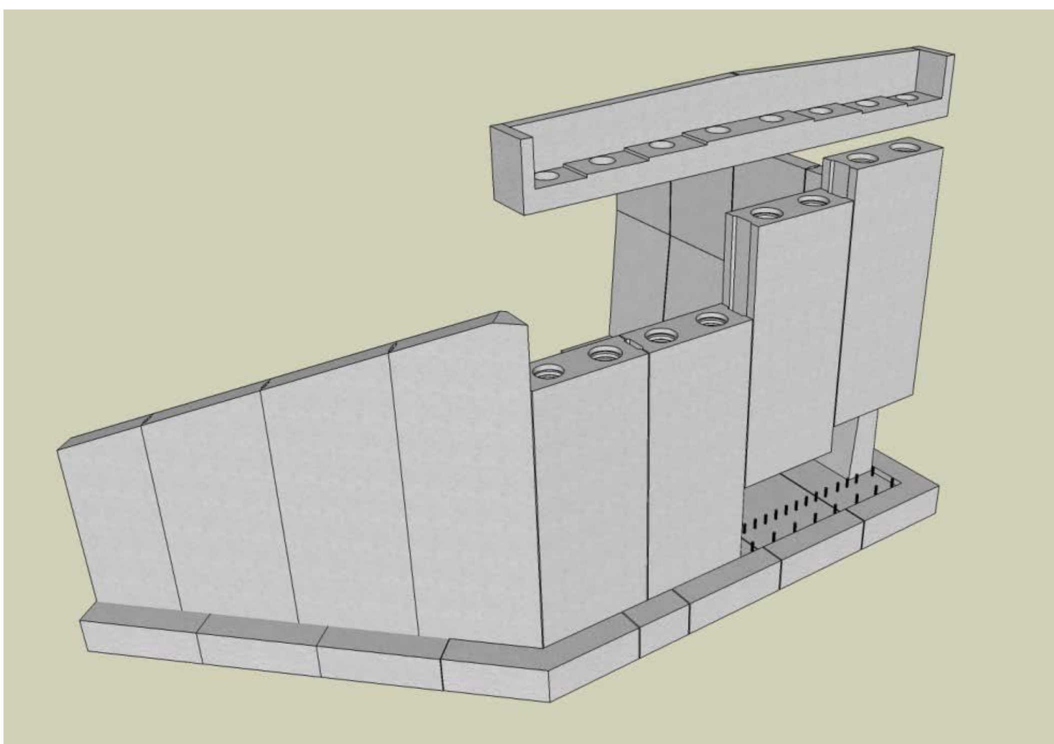


Figure 2-18: Prefabricated cantilever abutment [1]

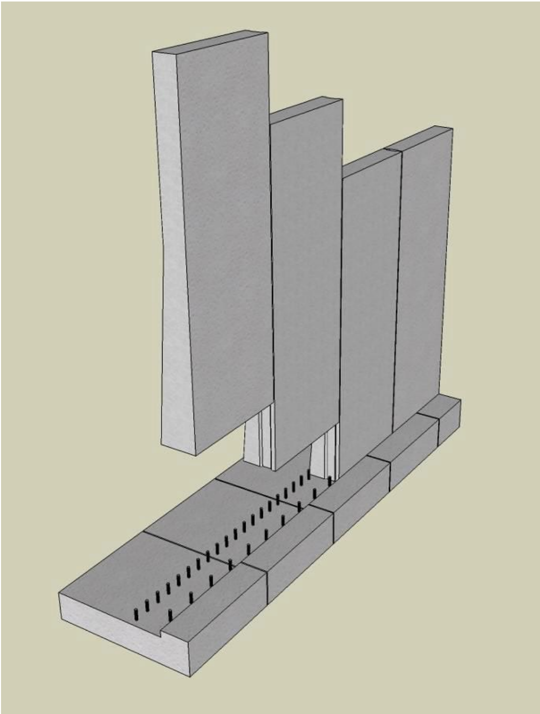


Figure 2-19: Prefabricated cantilever wing wall [1]

2.1.2.3 Pier cap

Pier caps provide enough space for sitting of girders to transfer loads from superstructure to substructure and distribute the loads from bearing to piers (Figure 2-20) [1]. The cast-in-place and the precast pocket connections are typically used to connect the columns to the cap. Other connection types have also been used for this purpose. Cap beams can be designed according to the displacement-based or force-based methods using AASTO LRFD bridge design specification. A linear elastic behavior for cap beams during the earthquake is necessary according to the specification [18].

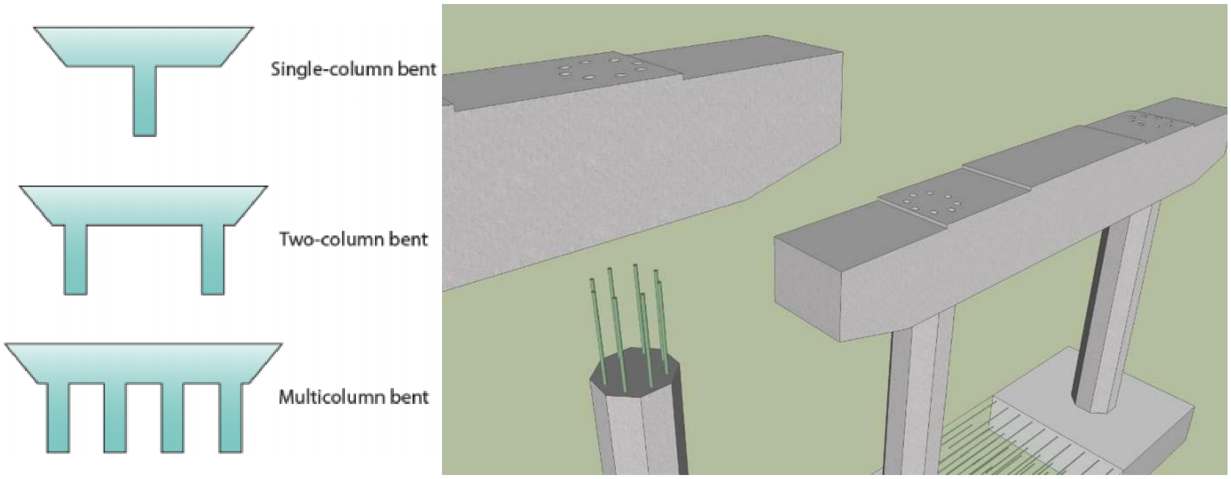


Figure 2-20: Typical type of pier cap [19]

There are two main types of pier caps; rectangular pier cap, and inverted-tee pier cap. Of these, the precast rectangular pier cap is used widely [3]. Rectangular pier cap is typically used when there is a precast girder or steel girder that can sit directly on top of the pier cap (Figure 2-21). The connection of pier cap to the pier can be fixed, pined, or isolated. The inverted-tee pier cap can be used when there are precast girders (Figures 2-22 and 2-23). However, there is a challenge with the seismic behavior of the tee edges to satisfy the required demand that should be considered in the seismic regions [19].

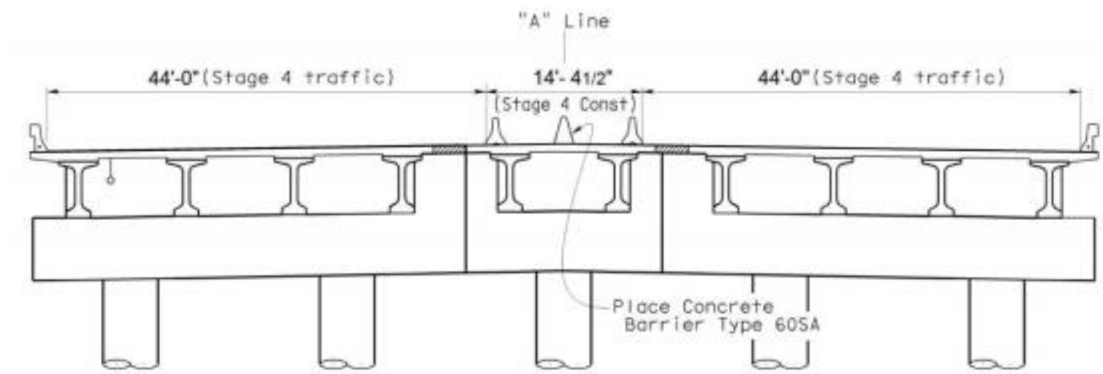
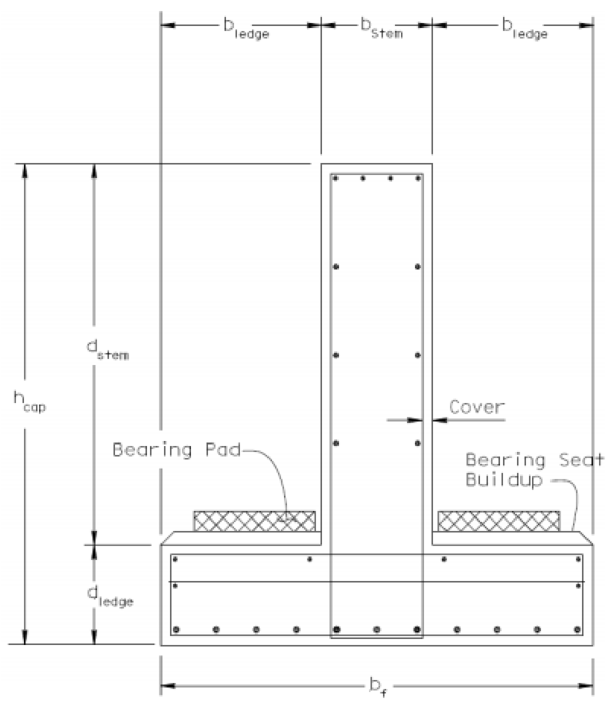


Figure 2-21: Rectangular pier cap [19]



b_{ledge} =	ledge width	d_{ledge} =	ledge depth
b_{stem} =	stem width	d_{stem} =	stem depth
b_f =	flange width	h_{cap} =	bent cap depth

Figure 2-22: Inverted-tee pier cap [19]

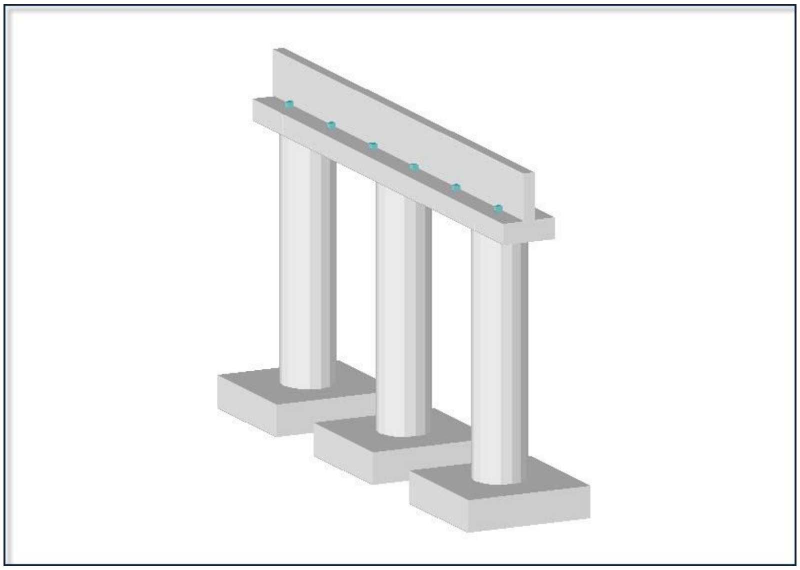


Figure 2-23: Inverted-tee pier cap [20]

2.1.3 Foundation

The function of a foundation is to transfer load from the abutment, pier, and wing wall to the earth strata [1]. It acts as an interfacing element between the superstructure/substructure and the underlying soil or rock. Selection of proper foundation is important to transfer load to the underlying soil without causing shear failure of soil or damaging settlement of the superstructure [21]. Therefore, it is essential to systematically consider various foundation types and to select the optimum alternative based on the superstructure requirements and the subsurface conditions. When the soil near the surface is adequately stable and can provide enough bearing for the bridge load, spread footings can be used as the bridge foundation. However, when the top soil is not stable enough, deep foundation such as piles should be considered under the footing to transfer the load into the hard strata and thereby provide enough support to the bridge structure. Also, in case of bridge construction in water, the bridge foundations should be deep enough to prevent scouring due to water current. To reduce the amount of construction time and impact on traffic flow, different precast prefabricated elements can be used in the foundation [1]. Different elements of foundation for accelerated construction include, but are not limited to the following:

- Deep foundations
- Prefabricated Spread Footings
- Prefabricated Caps for Caisson or Pile foundation
- Sheet Piling (Steel or Precast Concrete)
- Precast Pier Box Cofferdams

Details of the foundation elements are presented in the following section.

2.1.3.1 Precast Spread Footing

Spread footing should be considered as bridge foundation if competent soils are available within shallow depth. The width of spread footing is expected to be small and depth of footing should be economically feasible [21]. Shallow spread footings require significantly less time to excavate and place than deep foundations such as drilled or driven piles. If necessary, ground improvement methods can be used to improve the subsurface conditions for shallow spread footing [21]. Generally, spread footings are constructed using cast-in-place methods. However, precast spread footings are also available for bridge foundation. These footings are precast off-site, transported to the construction site and placed on a prepared subgrade and then grouted in place [22]. However, transporting precast concrete footings may be challenging as the size of footings can get quite large for bridge loads [1]. A new hybrid system can be applied which allows the installation of the footing at the speed of precast with the economy of cast-in-place. In such cases, a precast concrete footing is used only under the columns. A continuous footing is then obtained by using a cast-in-place closure pour on extended reinforcing bars from precast concrete footing during the erection of the remaining portions of the bridge [1]. The completed continuous footing is designed to support all other loads. Figure 2.24 presents a schematic of precast spread footing as bridge foundation.

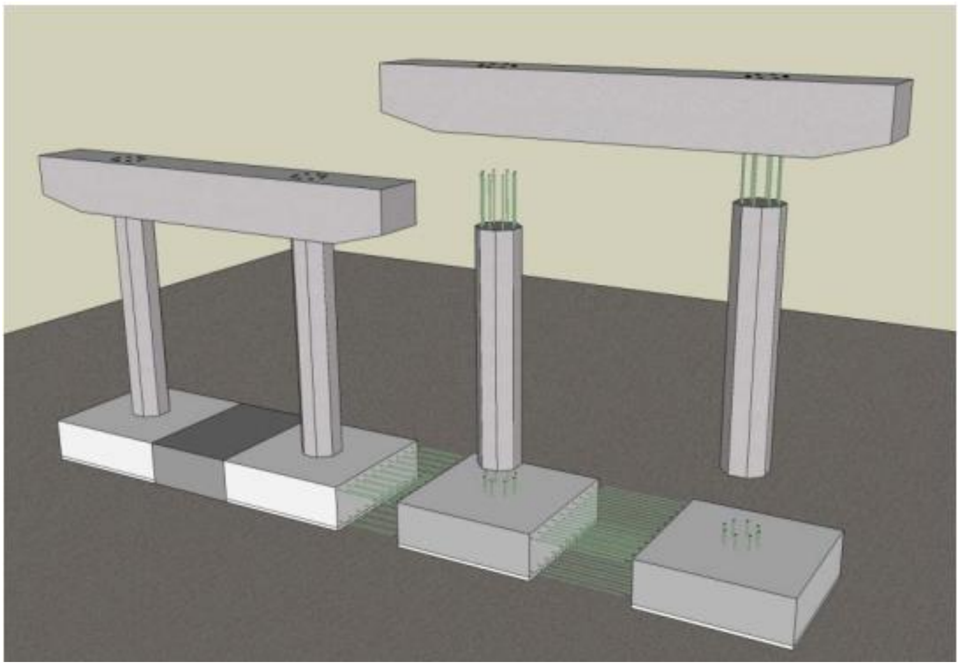


Figure 2-24 Precast spread footing as bridge foundation [1]

2.1.3.2 Deep Foundations

Deep foundations are selected when competent soils or rocks cannot be found on the top stratum or if there is a possibility of extensive scour, liquefaction or lateral spread [23]. Deep foundations are one of the most commonly used foundations for bridges by many state agencies [23-25]. Different types of deep foundations such as driven piles, micropiles, continuous flight auger (CFA) piles, or drilled shafts are frequently used as bridge foundation [26, 1, 23-25, 21]. Generally, a cap is built with the pile foundation to provide a stable platform for supporting substructure. Also, piles can be directly connected to the bent cap for short span bridges. Pile bents are cost effective and can be built quickly since there is no need for a footing. Most pile bents are constructed with precast concrete piles [1].

Driven piles are the most commonly used deep foundation system for bridge projects. These precast prefabricated foundation elements are installed in the ground using a pile driving hammer. Driven piles such as steel H, pipe, and prestressed concrete piles (Figure 2.25) with various section properties are available to support bridge structures [21].

Drilled shafts (Figure 2.26) are favorable and cost-effective for constructing foundation on cohesive soils, especially with deep groundwater. Large axial and lateral resistance can be obtained from drilled shaft when founded on a firm bearing stratum within 100 ft of the surface. Also, drill shaft foundation can be constructed at places with restricted access, low overhead and with a small footprint. The need for a concrete footing can be eliminated by using large diameter drilled shafts to support individual concrete pier columns [26].

The advantage of using CFA piles is that these piles are drilled and cast in place rather than driven into the ground (Figure 2.27). The CFA piles are formed by screwing a continuous auger into the ground and then grouting or concreting through the hollow center of the auger. The CFA is suitable for a wide range of cohesive and cohesionless soil conditions. Also, CFA does not produce shocks, vibrations, noise which makes it suitable for construction in urban areas [26, 1].

Micropiles are another type of drilled pile that are generally smaller in diameter (less than 12 inch), reinforced and grouted deep foundation element. Micropiles are typically used for underpinning, seismic retrofitting, and projects with difficult drilling conditions. These types of piles are suitable for places where small size and lightweight is advantageous or required because of the site constrains [26, 21].

Figure 2-25 Driven pile (prestressed concrete) as bridge foundation [21]

Figure 2-26 Drilled shaft piles as bridge foundation [26]

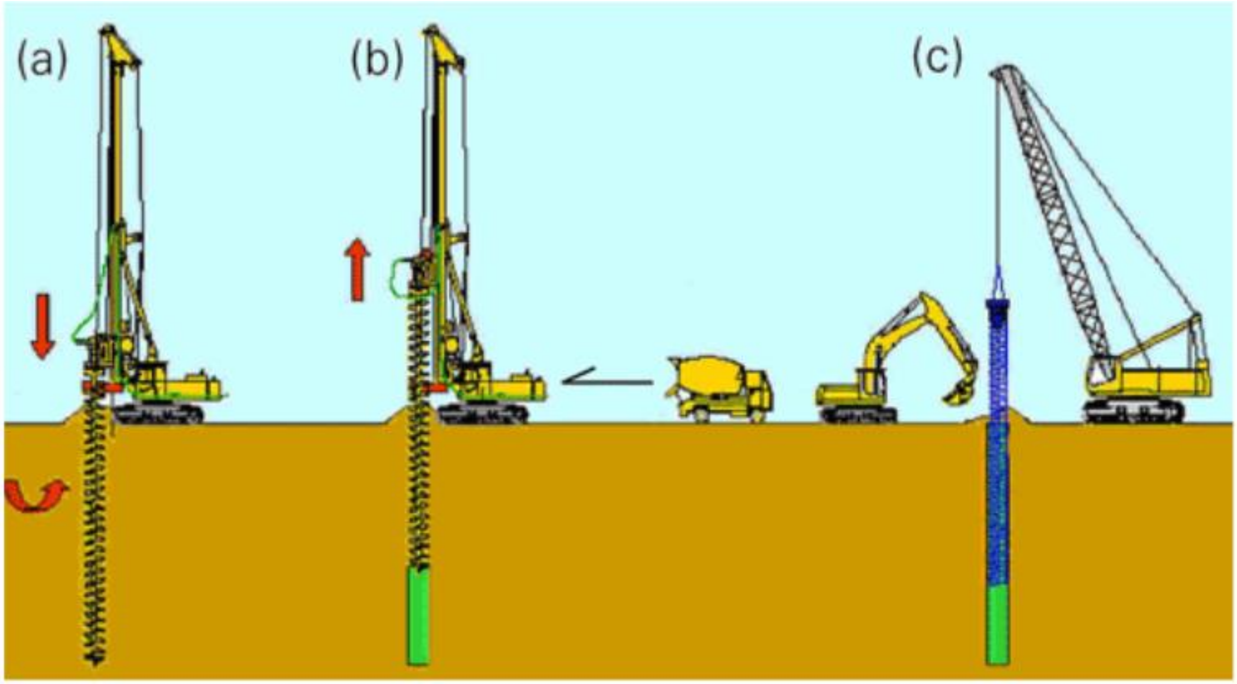


Figure 2-27 Continuous flight Auger pile as bridge foundation [1]

2.1.3.3 Pile Cap Footings

Precast concrete pile caps can be used when steel or concrete piles are left projecting above the ground line to support the superstructure/substructure. Generally, a pile cap is cast-in-place by pouring concrete around the projecting piles to provide support for the superstructure. However, a precast cap with grouted pocket connection can also be used instead of a cast-in-place pile cap.

The connection between the cap and the piles is achieved by filling the grout pockets with an epoxy grout [1, 22]. A number of different pile cap connections are detailed in the FHWA Connections Manual [2] to ensure punching shear and moment resistance at the connections. Figure 2.28 presents a sketch of precast concrete pile cap placed on precast concrete piles.

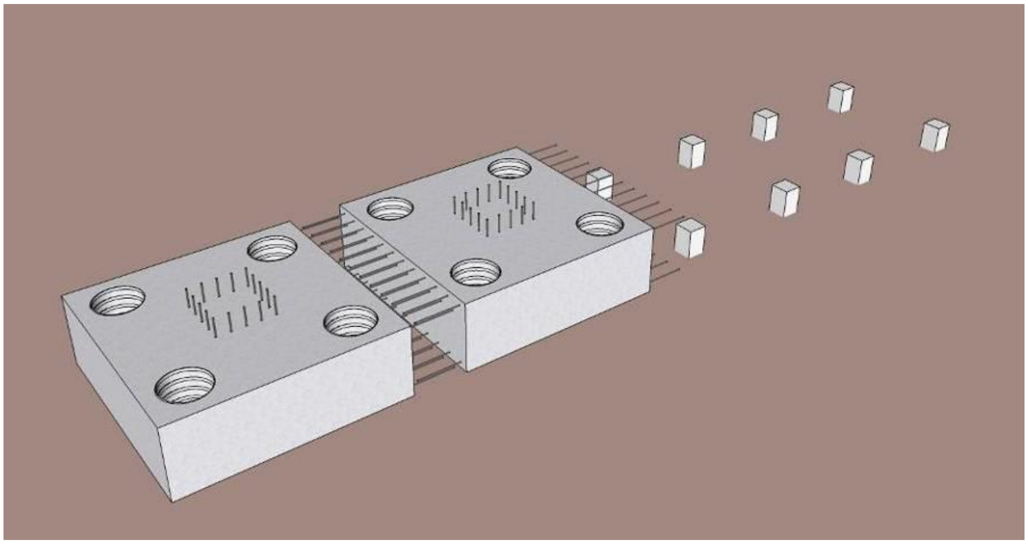


Figure 2-28: Prefabricated pile cap footing [1]

2.1.3.4 Precast Pier Box Cofferdams

In case of bridge construction in water, a precast concrete pier box is used to dewater the area where deep foundation connects to substructure. This structure can sit over the shaft and be sealed to provide a dry condition during construction of footing. Also, the precast pier box systems can eliminate the need for complicated cofferdams and dewatering systems. This prefabricating system can be floated downstream from the place of cast and set into place to block off water flow for the installation of the pile caps. Also, these can be used as an additional corrosion protection system for the new pier footing when built with high performance concrete. Additionally, significant savings in time and money in the construction of the foundations can be achieved by using the precast concrete pier boxes [1, 22]. Figure 2.29 presents a precast concrete pier box that allows construction of footings in a dry environment.

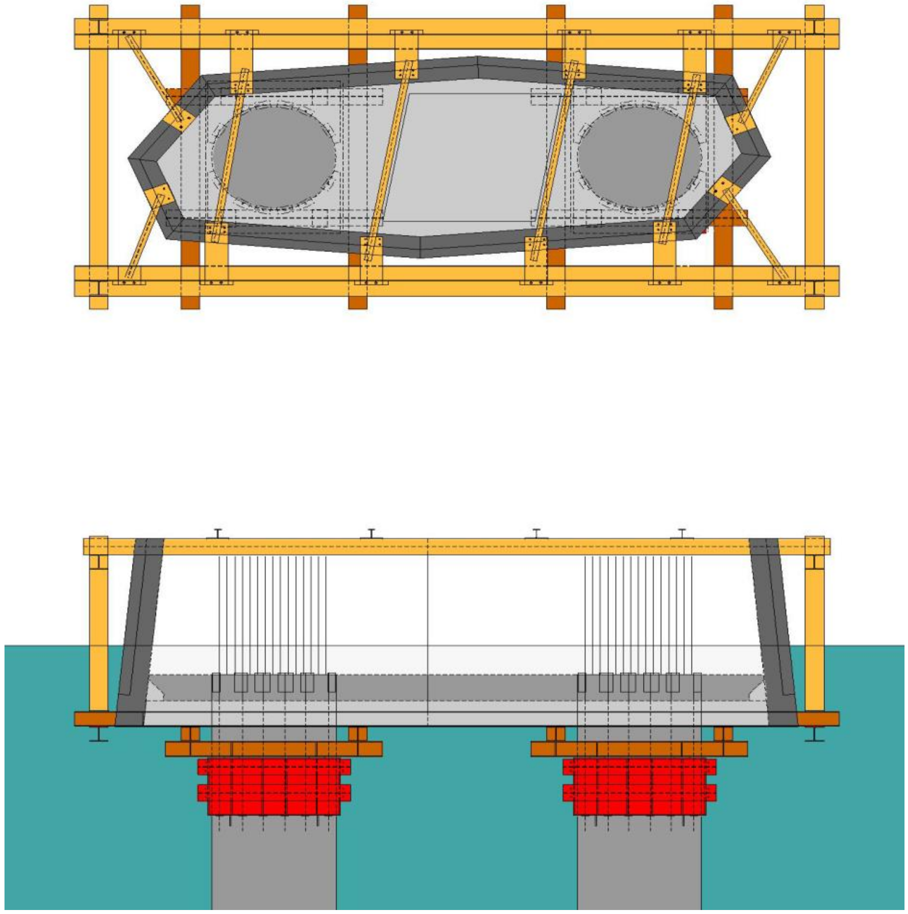


Figure 2-29: Precast concrete pier box cofferdam [1]

2.1.3.5 Precast Sheet Piling

Precast concrete sheet pile and cellular steel sheet piles are most commonly used sheet piling systems for foundation construction and excavation support. Standards for precast concrete sheet piling was developed by Florida DOT. Typically, two types of cellular sheet piles are available, namely closed cell sheeting and open cell sheeting [1]. These precast prefabricated elements can be used to accelerate construction of bridge piers and abutments.

A geotechnical engineering scan tour of Europe was organized by FHWA and AAASHTO in June 2002 to evaluate the use of different accelerated bridge construction technologies. Based on the findings from that scan tour, Dumas et al. [27] presented a comparison (Table 2.4) between bridge foundation systems, equipment, and ground improvement methods for poor subgrade. According to Dumas et al. [27], the standard of practice for bridge foundation construction in the U.S. is driven piles or drilled shafts as CFA piles were found to have problem with quality control/quality assurance. An alternative for rapid construction could be the use of CFA piles with automated computer control and automated QC/QA. Another alternate accelerated method suggested by the scan team was bored cased secant (CSP) piles which can be used for both bridge support and excavation support involving cut situations. Accelerated bridge construction technologies such as

Hydro-Mill and vibro-jet sheet pile driving method were found to be useful for rapid construction of bridge foundation.

Table 2-4 Bridge Foundation Systems, Equipment, and Ground Improvement Methods for Accelerated Construction on Poor Subgrades

Technology or process	**Anticipated accelerated Construction Performance**	**Related Potential for Accelerated Construction**	**Applicable conditions for Accelerated Construction**	**Relative Cost**	**Improvement in Quality**	**Comments**
Continuous Flight Auger Piles (CFA)	Rapid pile installation for vertical or batter piles	High	Best in weak to medium soil	Medium	Low	Automated control, Not suitable for difficult drilling
Bored Piling-Cased Secant Pile (CSP)	Rapid Pile installation for vertical piles	High	Cut situations, temporary excavations	Medium	Medium	Casing assists in some soil conditions
Self-Drilling Hollow Bar Nailing and Miro piling	Self-drilling and grouting for one-step installation	High	Difficult ground for drilling/driving	Low	High	Confined condition with difficult ground for drilling
Vibro-Jet of Sheet pile Driving	Speeds driving of sheet piles through layered soils	Medium	Same as conventional	Low	Low	Bridge abutments with grouting through vibro-jet pipes
Hydro-Mill	Rapid excavation of wall with no mess	Medium	Difficult drilling condition, large loads	Medium	High	Difficult drilling conditions, large loads and tight spaces
Screw piling	Requires 1/3 the time of auger cast piles	Low	Relatively weak soil conditions	Medium	Low	Auto control Depth<100ft Non-artesian

2.1.3.6 Geofoam Rapid Embankment System

The Geofoam Embankment System (Figure 2.30) constitutes an embankment formed by expanded polystyrene blocks [1]. Given their light weight property they are used for weak sub soils. Typically, a load distribution slab is built on top of the geofoam and covered with soil [52]. It usage is not predestined for a structural support system; the expanded polystyrene geofoam can also be placed around piles of an integral abutment or behind a conventional abutment [1].

Application of this technology is mainly for but not limited to reducing swell pressure of swell-type soils, reduce lateral earth pressure and reduction of settlement in embankments [52]. Moreover, benefits of this system include the elimination of pre-load settlement times, extremely lightweight material and fast construction [1].

The design considerations for this system is straightforward. Site is leveled, and layer of bedding sand needs to be placed. Geofoam are then placed with bedding sand that will fill the gap between backslope and geofoam. A load distribution slab is placed on top of the geofoam and then a layer of fill over the slab, and finally covered by the pavement [53].

Figure 2-30: EPS Geofoam Embankment (Source ACH Foam Technologies)

2.1.3.7 Geosynthetic Reinforced Soil (GRS) Integrated Bridge System

GRS refers to an innovative geotechnical system that combines properties of granular soil and geosynthetic material to improve strength and stiffness of a soil mass. GRS systems are somewhat analogous to reinforced concrete. Both plain concrete and soil perform adequately in compression and shear, but lack strength and ductility in tension. The addition of rebar in concrete and geosynthetics in soil improves performance of both materials. GRS systems were shown to have a beneficial application to short-span bridges in recent years [28]. The GRS needs to be finished with a beam seat or cap to receive the superstructure. Figure 2.31 shows an example of GRS/IBS Bridge abutment.

A recent form of abutment system is the Geosynthetic Reinforced Soil Integrated Bridge System (GRSIBS), which is described in FHWA publication *FHWA-HRT-11-027* (Adams et al. 2011). This is a relatively new abutment system that has been used for accelerated bridge construction, and typically for short spans up to about 140 feet. The abutment uses alternating thin layers of compacted fill and geosynthetic reinforcement sheets that combine to form a reinforced soil mass foundation that directly supports the bridge superstructure without the need for piles. The geosynthetic reinforcement is connected into layers of precast facing blocks that are placed with the reinforcement and soil backfill. Once completed, the reinforced soil mass is ready to support the bridge. Traditional abutments are typically concrete construction. When deep foundations are required to support the bent caps, they normally consist of timber, prestressed concrete square, solid round or hollow cylinder piles, CIP concrete drilled shafts, or steel HP or pipe pile sections [54].

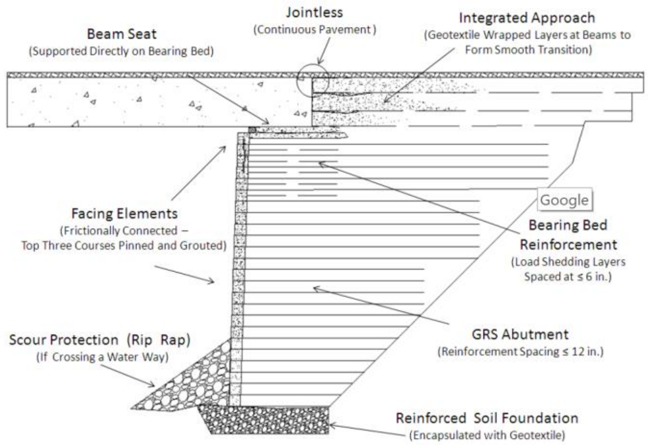


Figure 2-31: Typical Section of a GRS/IBS Bridge abutment [1]

2.1.3.8 Mechanically stabilized earth retaining walls

Mechanically Stabilized Earth (MSE) retaining walls are very common in the U.S. They are comprised of precast concrete panels connected to reinforcing strips that are embedded into the backfill soils. Figure 2.32 shows a cross section of a typical MSE wall. The use of MSE accelerates the construction of walls since the curing of concrete is minimized (footing only), and backfilling and erection of the wall occur in parallel. MSE walls function by engaging the soil mass behind the wall face to form an earth gravity wall system [7].

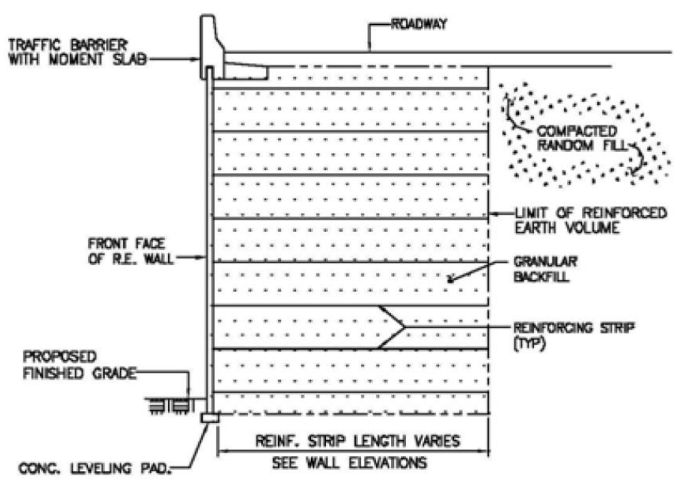


Figure 2-32: Typical Mechanically Stabilized Earth Systems (MSE) Wall Details [1]

There are also wall systems that use GRS fabric, wire mesh or natural vegetation in place of the wall panel facings. The construction of these walls can progress rapidly because the system is built while the soil is being placed behind the wall; thereby combining two processes into one [1].

Many states also use MSE walls for abutments; however, the walls typically do not support the bridge. Piles or drilled shafts are installed prior to wall construction. The MSE wall is then typically built in front of the piles with the reinforcing strips placed between the piles. Once complete, a concrete footing is installed on top of the piles, creating two separate structures [7].

2.1.4 Systems and Subsystems

In construction of bridge, it is sometime more efficient to assemble prefabricated elements off-site or combine several elements (e.g., deck with girder) to further reduce the time of construction and provide a better quality. In some cases, structural elements and miscellaneous elements of a bridge can be prefabricated together. These systems are summarized in Table 2-5 and described as follow.

In some cases, a larger portion of the superstructure is constructed normally near the site and moved in place onto the substructure. Sometime, the entire length and width of the bridge superstructure, with or without miscellaneous elements, is prefabricated and installed onto the substructure using one of the installation methods such as lifting, SPMT, and sliding horizontally or transversely. In some instances, entire superstructure is fabricated with part or all the substructure and moved or placed on the footing. Prefabricated superstructure elements and systems are summarized in Table 2-5.

As an alternative to traditional bridges, buried bridges can sometime offer economic solution, especially for hydraulic and minor road crossings. A buried bridge is a buried structure supporting a roadway that relies on the support from the soil-structure-interaction. The design and installation of buried bridges have evolved over the years to accommodate longer spans inclusive of the range for short-span bridges. Since major segments, sometimes the entire superstructure and substructure, are prefabricated away from site and installed in place, they certainly qualify as ABC bridges. Furthermore, it qualifies as ABC Systems or Subsystem in that it often combines superstructure and substructure. Although culverts that are defined with spans of less than 20 ft may not count ass bridges, but for completeness, culverts are also reviewed here briefly. They certainly combine substructure, and for the case of boxes the foundation, with the superstructure as a system.

Table 2-5: Different ABC bridge systems and subsystems

System	Type	Comment
Modular superstructure systems	Modular steel systems	Different modular steel systems include multi-beams unit, modular steel folded plate girder system, and orthotropic steel deck system
	Precast concrete modular systems	Different precast concrete modular systems include double tees and decked bulb tees.
	Modular timber system	All the elements are prefabricated. The laminated girder deck system is installed on the top of timber or steel beam.
Complete bridge superstructure subsystem	Entire width of superstructure with or without miscellenous elements	The superstructure can be entirely fabricated off-site and moved to be installed on site
Complete bridge system	Superstructure with integral piers	The entire width of superstructure can be constructed along with part or entire substructure and moved or slid on footing
Substructure subsystem	Piers with column and footing	The column piers and column can be constructed together or along with footing
Buried bridges	In the form of three-sided or full box, or arhc systems covering spans larger than 20 ft	Their design accounts for support from surrounding soil. They are normally used for remote site access, aquatic crossings, pedestrian tunnels, temporary detours, and it can support heavy live loading for trucks, mine vehicles, etc.
Culverts	Three-sided or box system for spans smaller than 20 ft	Normally to accommodate the flow of stormwater and sewage.

2.1.4.1 Modular Superstructure Subsystems

The modular superstructure system is an integral fabrication of deck panels, girders, and their connections together. In this system, the panels are connected to each other at the edges using grouted shear connector pockets (shear keys) [1]. To pour the closures and pockets, a low shrinkage pour should be used to prevent transverse cracking. The limitation in the dimension of the modular systems is controlled by their heavy weight and long length that can make their shipping difficult. Therefore, the modular steel system is more desirable than modular precast concrete systems due to its light weight.

Modular steel systems can be topped multi-beams unit, modular steel folded plate girder system, or orthotropic steel deck system. Topped multi-beams system includes two or three steel beams that are topped with reinforced concrete (Figure 2-33) [1]. Another system is the modular steel folded plate girder that in its current form can be used for short span bridges with a maximum span of 60 feet (Figure 2-34) because of camber limitation. This system has a tube section built by bending of a flat plate. The advantage of this system is its stability. It does not require any external or local frames [29]. A new folded plate girder is under investigation by Accelerated Bridge Construction - University Transportation Center (ABC-UTC) that promises spans as long as 100 ft. or longer [30]. Orthotropic steel deck system is another modular steel system that can be fabricated in the form of single span orthotropic with the running of ribs on the deck span or orthotropic T beam. In orthotropic T beam system, steel girders and a portion of the orthotropic deck are used together as shown in Figure 2-35. The disadvantage of the orthotropic system is its high cost. The FHWA is developing a standardized method and technique for the construction of modular orthotropic systems to reduce cost [1].

Modular precast concrete superstructure systems include double tees and decked bulb tees. A double tee modular system includes two girders connected with a deck slab as shown in Figure 2-36. In the double tee modular superstructure, the adjacent beams normally connect to each other using the shear key connection. Bulb tee system consists of a girder with an extended top flange. In the bulb tees systems, the connection of two adjacent bulb tees is normally established using the welded tab connection. This type of connection limits the use of this system to low volume roads due to the low durability of the connection [1].

Another modular superstructure system is the modular timber elements system (Figure 2-37). In this system, all the elements are prefabricated, and the laminated girder deck system is then installed on the top of timber or steel beam.

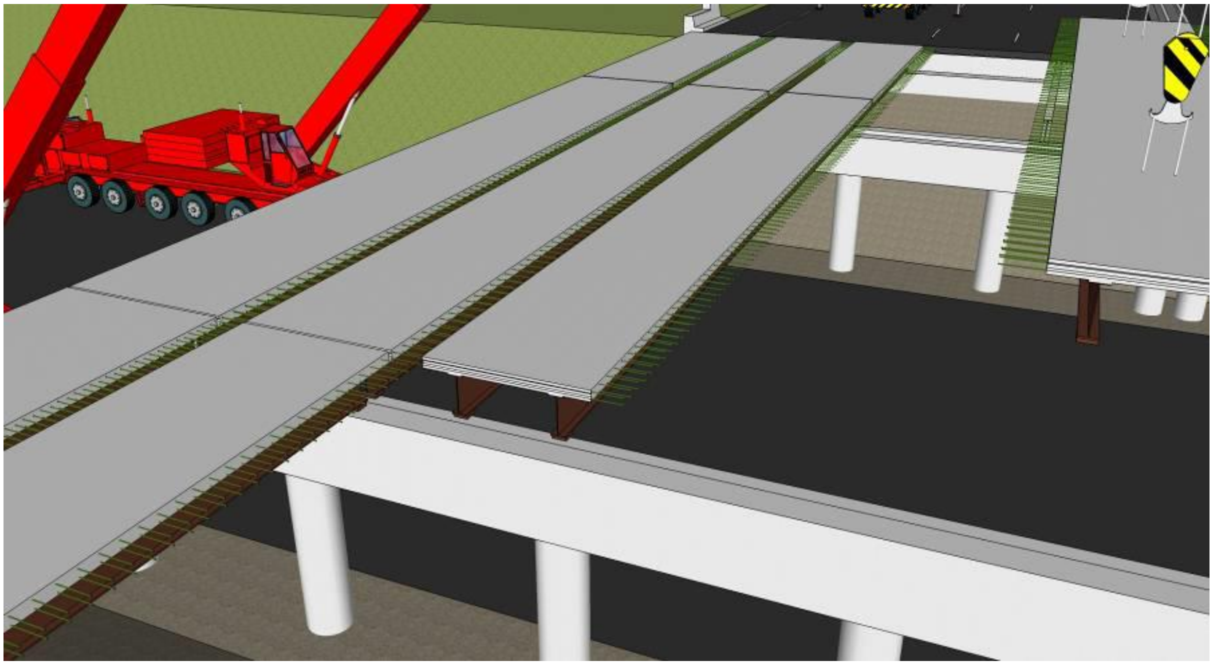


Figure 2-33: Modular steel superstructure system [1]


Figure 2-34: Modular steel girder; I-beams (left) [1], Folded plate (right) [29]

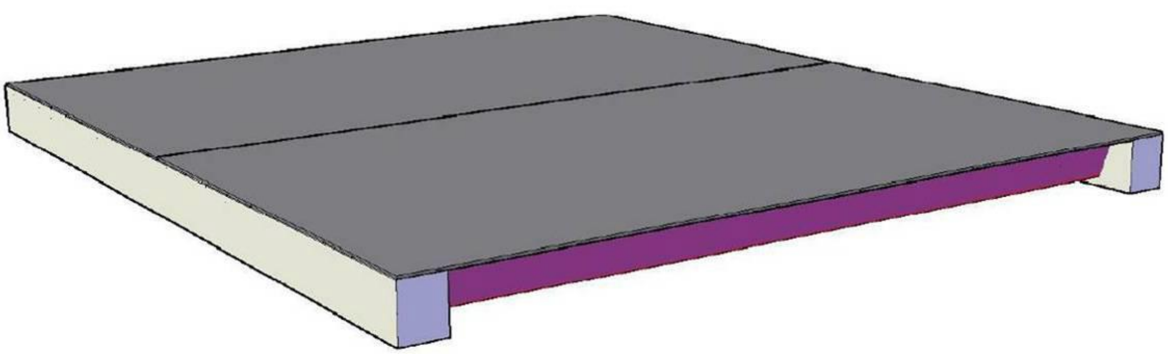


Figure 2-35: Modular orthotropic superstructure system [1]

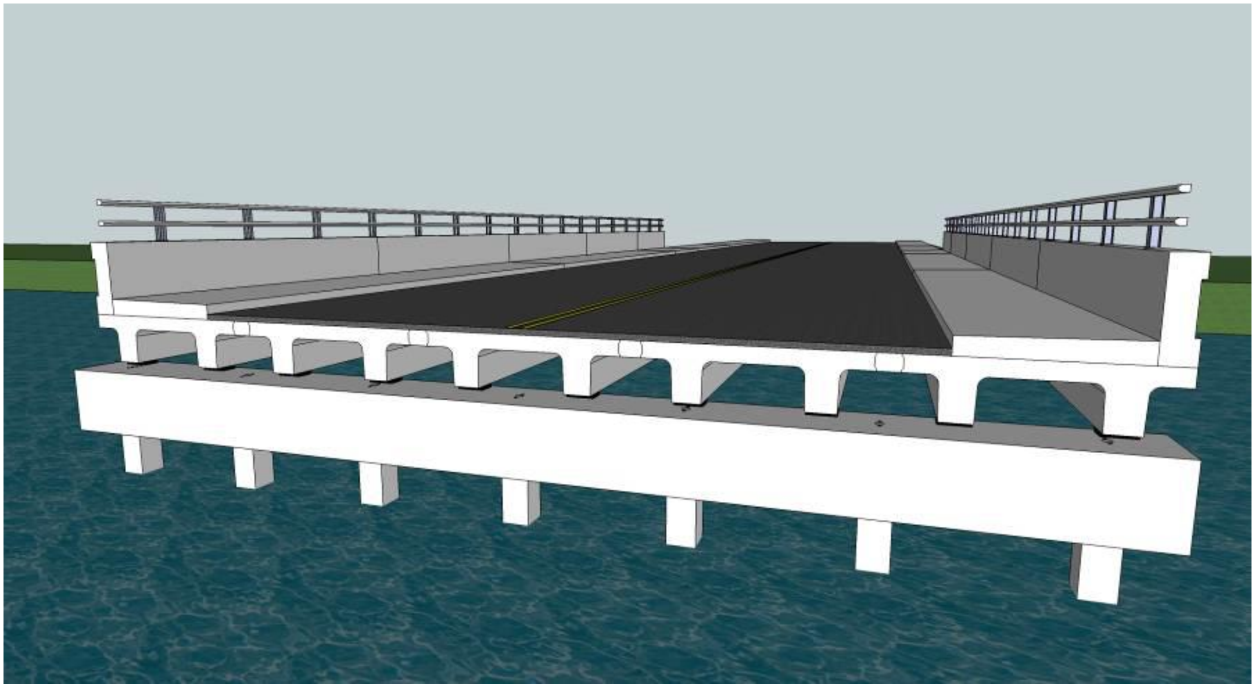


Figure 2-36: Modular double tee superstructure system [1]

Figure 2-37: Laminated timber deck system [1]

2.1.4.2 Buried Bridges (20 ft< Span < 70ft)

A buried bridge is a buried structure supporting a roadway that relies its support from the soil-structure-interaction with a bridge length greater than 20 feet [28]. The design and analysis methods consider the static soil-structure interaction and that gives the reason of the use of the term buried. As these structures have a span length that exceed 20 ft and in some cases approach 100-foot span therefore the term bridge is utilized. As the same case for conventional bridges, buried bridges can be used for new bridges, existing bridges and bridge reparation [28]. Buried bridges can be used for a variety of reasons, including but not limited to remote site access, aquatic crossings, pedestrian tunnels, temporary detours, and it can support heavy live loading for trucks, mine vehicles, etc. [28].

Implementation of Accelerated Bridge Construction is possible with buried bridges as installation can be done in a relatively short time (days) basis reducing onsite manpower and expertise for installation. Additionally, accelerated design and installation process can be also guaranteed with availability of many standard designs, rapid shop fabrication and minimum material shipment needed. This type of bridge can improve environmental characteristics and sustainability as onsite material can be used for backfilling. Maintenance decreases as there is no bridge deck and no expansion joint. Reuse of existing foundations are possible and foundation settlement tolerance is increased.

In order to select buried bridge geometry, evaluation of durability, and adequate soil-structure interaction parameters are considered through the evaluation of the function and site constraints for the design. Size of the structure can be defined by rise and span (Figure 2.47) and different types can be determined by the hydraulic opening or clearance envelope. Length on the other hand, can be determined by the roadway width, end treatments or waterway placement [28]. These different types of geometry can be classified into reinforced concrete and corrugated metal geometry as they are in Table 2.6.

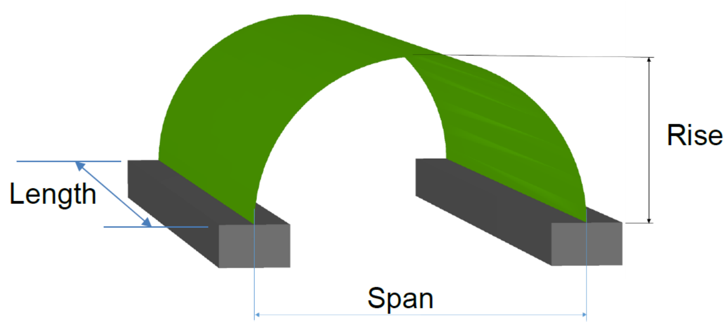


Figure 2-38; Buried Bridge Structure Geometry [31]

Table 2-6: Buried Bridge Geometry [31]

SHAPE	RANGE OF SIZES	COMMON USES
REINFORCED CONCRETE		
RECTANGULAR (BOX)	Span 8 ft to 48 ft	Culverts and Short-span bridges.
THREE-SIDED	Span 8 ft to 48 ft	Culverts and Short-span bridges.
ARCH	Span 15 ft to 102 ft	Culverts and Short-span bridges For low, wide waterway enclosures, aesthetic bridges

SHAPE	RANGE OF SIZES	COMMON USES
CORRUGATED METAL		
ARCH (SPAN, RISE)	Span x Rise 5 ft x 1 ft 9.5 in. to 82 ft x 42 ft	Culverts and Short-span bridges, Low clearance waterway, aesthetic bridges
HIGH PROFILE ARCH (SPAN)	Span 20 ft To 83 ft	Culverts and Short-span bridges, Grade separations, Ammunition magazines, earth covered storage
BOX (SPAN)	Span 10 ft To 53 ft	Culverts and Short-span bridges

2.1.4.2.1 Reinforced Concrete

Use of plant precasting of standardized sections is another way in which accelerated bridge construction can be implemented. Several manufacturers have developed precast concrete box, three-sided, and arch systems. These systems can be filled with onsite or granular backfill. Sometimes, these structures can be slid under existing bridges without interrupting existing roadway. Voids between both structures can then be filled with or without removal of existing bridges [1].

2.1.4.2.1.1 Rectangular (Box):

- Span range of 8 ft to 48 ft,
- Common uses: culverts and short span bridges

A variety of sizes, depths and for different live loads are offered in precast concrete box buried bridges. The speed of construction is one of the major advantages when using a precast concrete box [32]. An example of a rectangular (box) buried bridge can be seen in Figure 2.39.

Figure 2-39: Rectangular (box) buried bridge [31]

2.1.4.2.1.2 Three-Sided:

- Span range of 8 ft to 48 ft,
- Common uses: culverts and short span bridges

Three-sided structure was created by a change in the design of the box culvert by removing the floor slab, this was done so it could comply with some environmental restrictions. Therefore, this type of design is used when there is limitation with hydraulic and environmental challenges in some states [33]. Figure 2.40 is an example of three-sided buried bridges.

Figure 2-40: Three-sided buried bridge [31]

2.1.4.2.1.3 Arch:

- Span range of 15 ft to 102 ft,
- common uses: culverts and short span bridges. For low, wide waterway enclosures, aesthetic bridges

Another environmentally friendly, bottomless option is the arch. Depending on the span length arches can come in one or two pieces. As is the case in Figure 2.41 where a longer span is needed the tow piece arch rebar from each element is tied together at midspan [33] (Figure 2-42).

Figure 2-41: Arch System[31]

Figure 2-42: Arch buried bridge[31]

2.1.4.2.2 Corrugated Metal

Several corrugated metal plates are bolted together to form these bridge systems [33]. Corrugated Metal Buried bridges are defined below:

2.1.4.2.2.1 Arch:

An Arch is a curved-shape structure that works in compression primarily and does not have a floor slab. This type can be effectively used where natural aquatic organism passage is necessary [32]. Figure 2.43 have different examples of arch buried bridge usage.

Figure 2-43: Corrugated Metal Arch buried bridges [31]

2.1.4.2.2.2 High Profile Arch:

The difference between a regular arch and a high-profile arch is that its high-rise dimensions are for larger flow volumes or where there are not clearance restrictions that could govern a specific structure selection. This type of structure is available in steel and aluminum and has an elliptical shape [33]. Figure 2.44 possesses many examples of high-profile arch buried bridges.

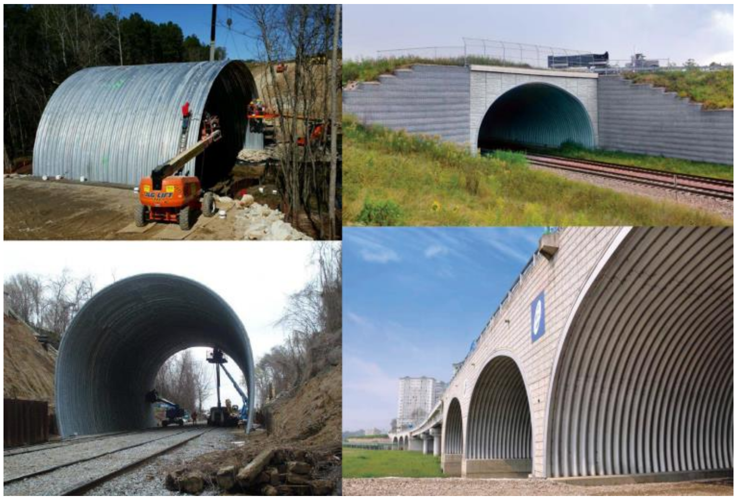


Figure 2-44: High Profile Arch buried bridges [31]

2.1.4.2.2.3 Box Shapes

Figure 2.45 is an example of box shapes. It can be observed that is neither arch shaped nor rectangular, but uses a flat top with rounded corners, allowing the metal plates to make the geometric transition [33].

Figure 2-45: Example of metal corrugated box [31]

2.1.4.3 Culverts

Culvert is used to accommodate the flow of stormwater and sewage. Precast arch structures, box culverts, and corrugated steel arch pipes are used commonly in the bridge construction with shorter spans [1]. To design and construct a precast culvert, standard specification of ASTM C5177 entitled “Precast Reinforced Concrete Monolithic Box Sections for Culverts, Storm Drains, and Sewers Designed According to AASHTO LRFD” can be used (Figure 2-46) [12]. Culverts can be four-sided (box), three-sided or arch section. Concrete box culvert has a rectangular cross-section [34]. Three sided culverts have a rectangular cross-section with varying wall thickness or have an arched structure. Three sided or arched culverts need a separate foundation to support them (Figure 2-47) [34]. In arch sections, the precast strips are placed side by side to create the bridge span and then filled with a granular embankment. The arch culverts can be slid under the existing bridge without closing the bridge.

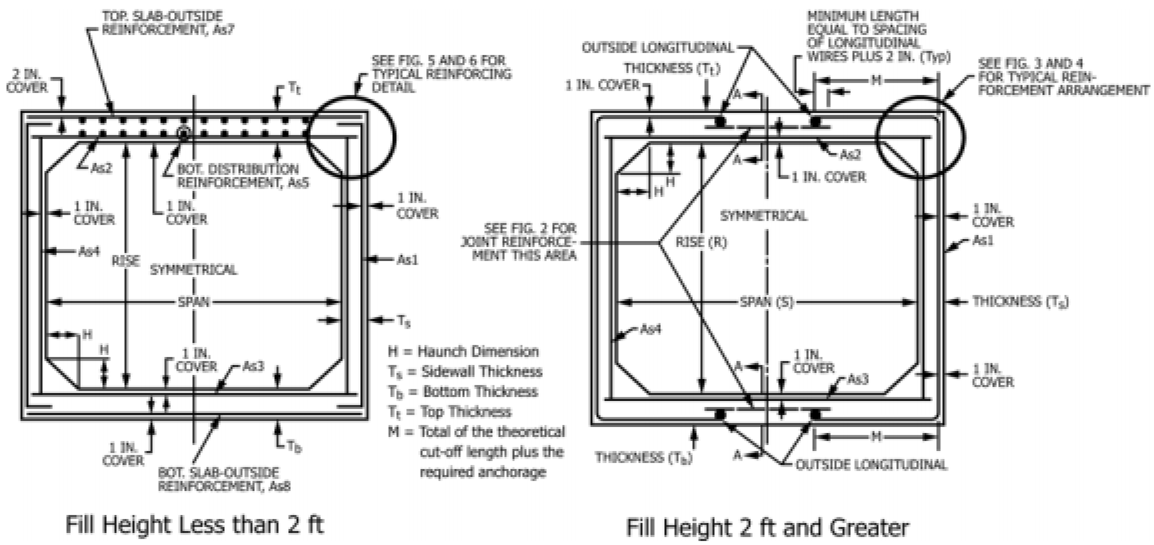


Figure 2-46: Precast box culvert section [12]

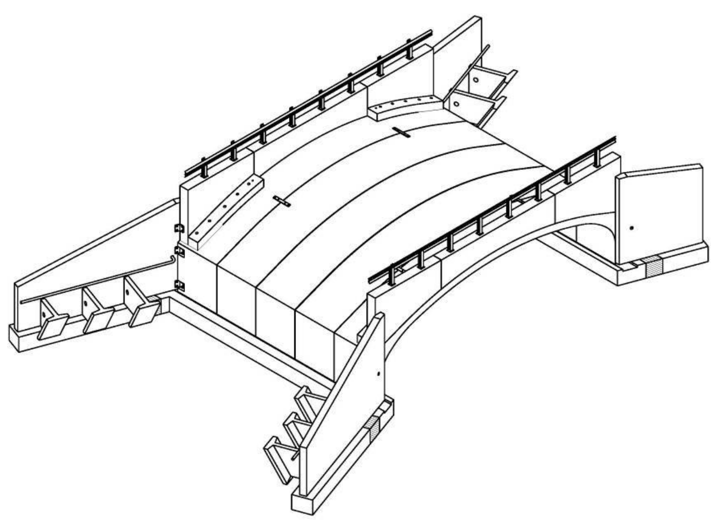


Figure 2-47: Arch culvert [1]

2.1.5 Joints and Connections

In ABC bridge construction, joints and connections are needed to attach the prefabricated elements to each other as well as between foundation, substructure, and superstructure (Figure 2-48). The design and details of joints and connections in bridges that use prefabricated elements should at a minimum satisfy the same conditions as connections in cast-in-place bridges to provide enough durability and integrity for the structure [35]. "Emulating connection detailing" and design is used to make the precast structural elements behave as if they are monolithic [36]. Accordingly, various connection types have been developed and validated for prefabricated elements including welded ties, mechanical couplers, small closure pours, closure joints, socket and pockets, and grouted tubes with reinforcing dowels.

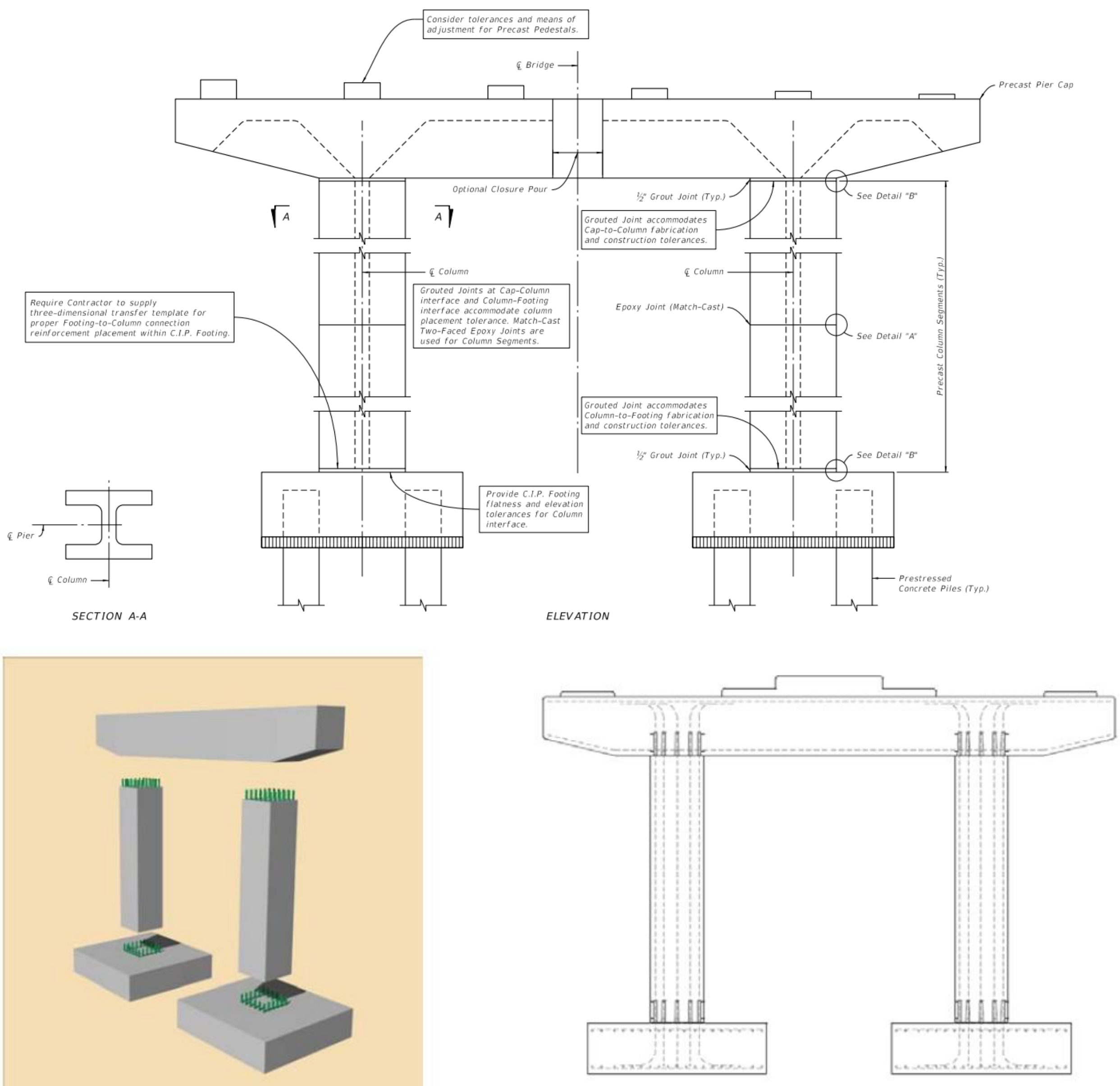


Figure 2-48: Prefabricated bridge connections [2]

2.1.5.1 Superstructure element connections

Joints connecting deck elements to each other and deck to the piers or girders are generally referred to as closure joints (Figure 2-49). The function of these joints is to prevent vertical movement of panels and transfer traffic load [1]. This joint can experience normal load, shear load, and bending moment.

Shear keys are used for connecting full-depth precast adjacent panels to each other. There are two types of shear keys including non-grouted male-female and grouted female-to-female joint [2]. In non-grouted joints, the longitudinal post-tensioning rebar is used to connect the panels and keep them together (Figure 2-50). In this connection, some sealant or epoxy is used at the interface before post-tensioning is applied. In grouted female to female joints, none-shrink grout is typically used to fill the joint (Figure 2-51). This type of connection performs properly if no cracks occur in the connection due to shrinkage and repeated service load, and if no water leakage occurs through the joint [37]. Moreover, the longitudinal reinforcement in panels can be spliced or doweled within the joints to distribute the live load from the traffic, and to resist shear and bending moment [2] (Figure 2-52).

Pockets left in the precast panels, blockouts are used to connect the precast panel to concrete girders. Reinforcement or shear studs extended out of the girder and embedded into the pockets to transfer shear between two connected elements (Figure 2-53). This connection is easily accessible. It can experience high shear and bending moment and little deformation. The connection of precast deck panels to girders and piers can be established through linear closure joints that also include headed steel studs [37]. Rectangular and V-shaped closure joint, with or without reinforcement or post-tensioning are also used to connect deck panels to each other, girder, and piers. Another type of connection that joins precast concrete girder and deck is with the use of drilled holes. After placement of deck, a hole is drilled into the deck and girder to to provide a conduit for dowel-type connection. This drilling is mostly not a problem for prestressed girders because the girder bars are located at the bottom of girder [2].

In summary, according to the joints configuration, the most common closure joints are categorized into five types [38]. These five categories are shown in Table 2-7. The first four shapes cover “linear” joints, and the last shape covers “blockouts.” Linear joints refer to longitudinal and transverse joints for connecting deck panels or decked beams to each other and to the girders, and connecting deck panels to the abutment/piers. Blockouts are pocket-type joints mostly for connecting deck panels to the girders [2].

In addition to the above common joints, other connecction types are also used for specific cases. Welding is one type of connection that can be used to connect panels to steel girder. This connection is preferable for ABC bridge construction because it can be erected quickly. Before installation of the panel, a steel plate is placed in a specified location of the panel, and then the steel girder and the panel are welded together in the field [2].

Prefabricated units can also be joined together using bolted connection. One use of the bolted connection is for establishing transverse connection between modular double tee units. The adjacent diaphragm plates are also bolted together [2].

One issue in the construction of superstructure is irregularity in the finished surface of panels due to inconsistencies in the panels or their supporting members. One way to address this issue and level the adjacent panels is to use a leveling device (Figure 2-54). In this case, a threaded socket is cast in the corner of each panel. Then the bolt is threaded in the socket and wrench to adjust the elevation of panels [5].

Figure 2-49: Examples of deck closure joints [2]

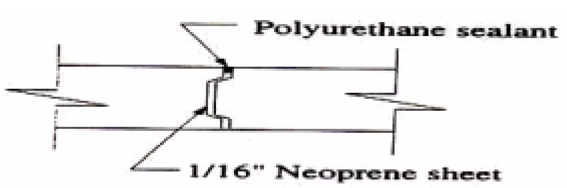
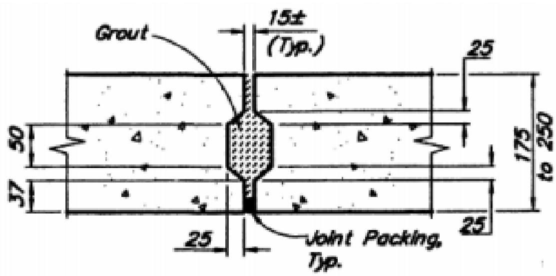
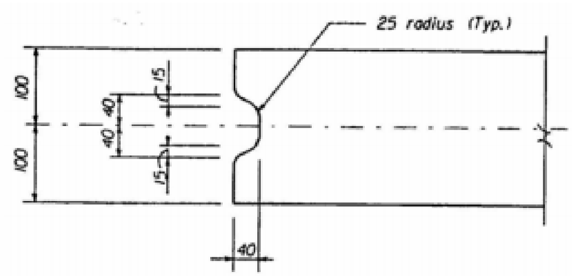


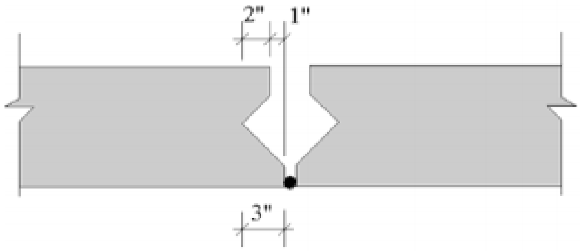
Figure 2-50: Non-grouted panel to panel (male-to-female) joint [37, 5]



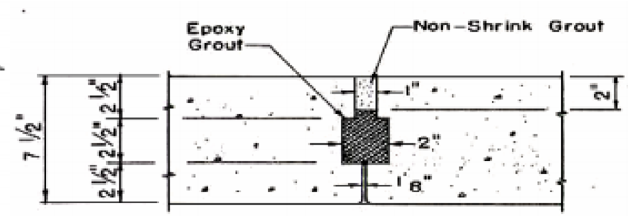
(a) Trapezoidal-shape shear key detail used in the Pedro Creek Bridge, Alaska



(b) Semi-circle shear key detail used in the George Washington Memorial Parkway Bridges, Washington DC



(c) V-Shape shear key detail used in the Skyline Drive Bridge, Omaha, Nebraska



(d) Rectangular shear key detail used in the Delaware River Bridge, New York

Figure 2-51: Various type of female-to-female joint [37]

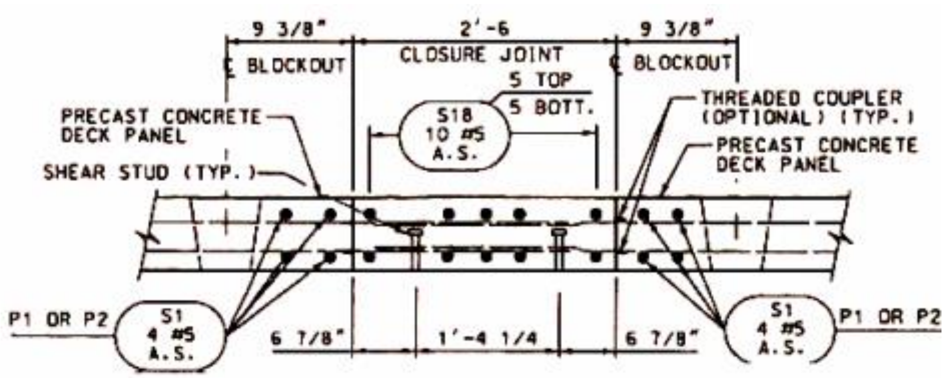


Figure 2-52: Longitudinal reinforcement [37]

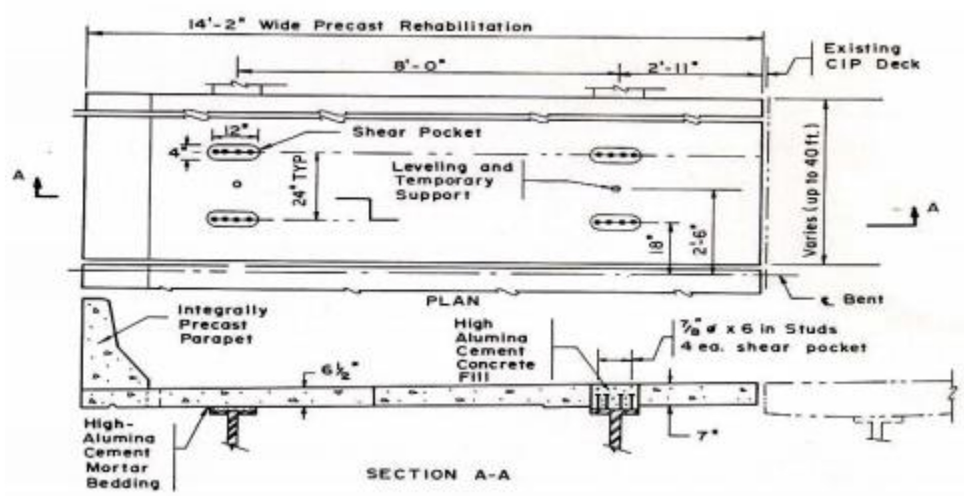
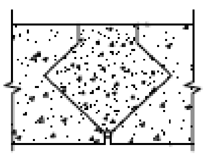
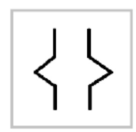
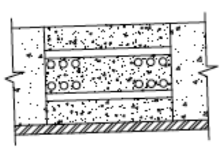
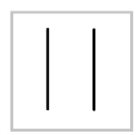
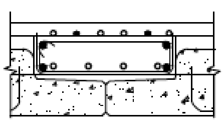
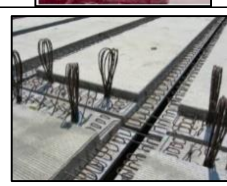
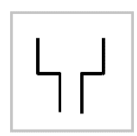
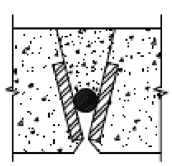
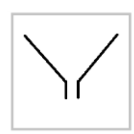
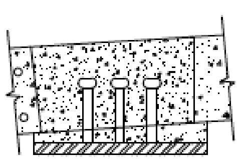
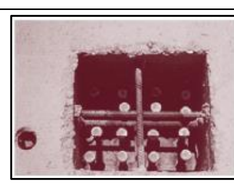
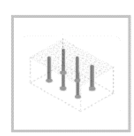


Figure 2-53: Panel to girder connection detail [37]

Table 2-7: Different type of closure joints [38]

Group	Sample		Symbol
Type 1			
Type 2			
Type 3			
Type 4			
Type 5			

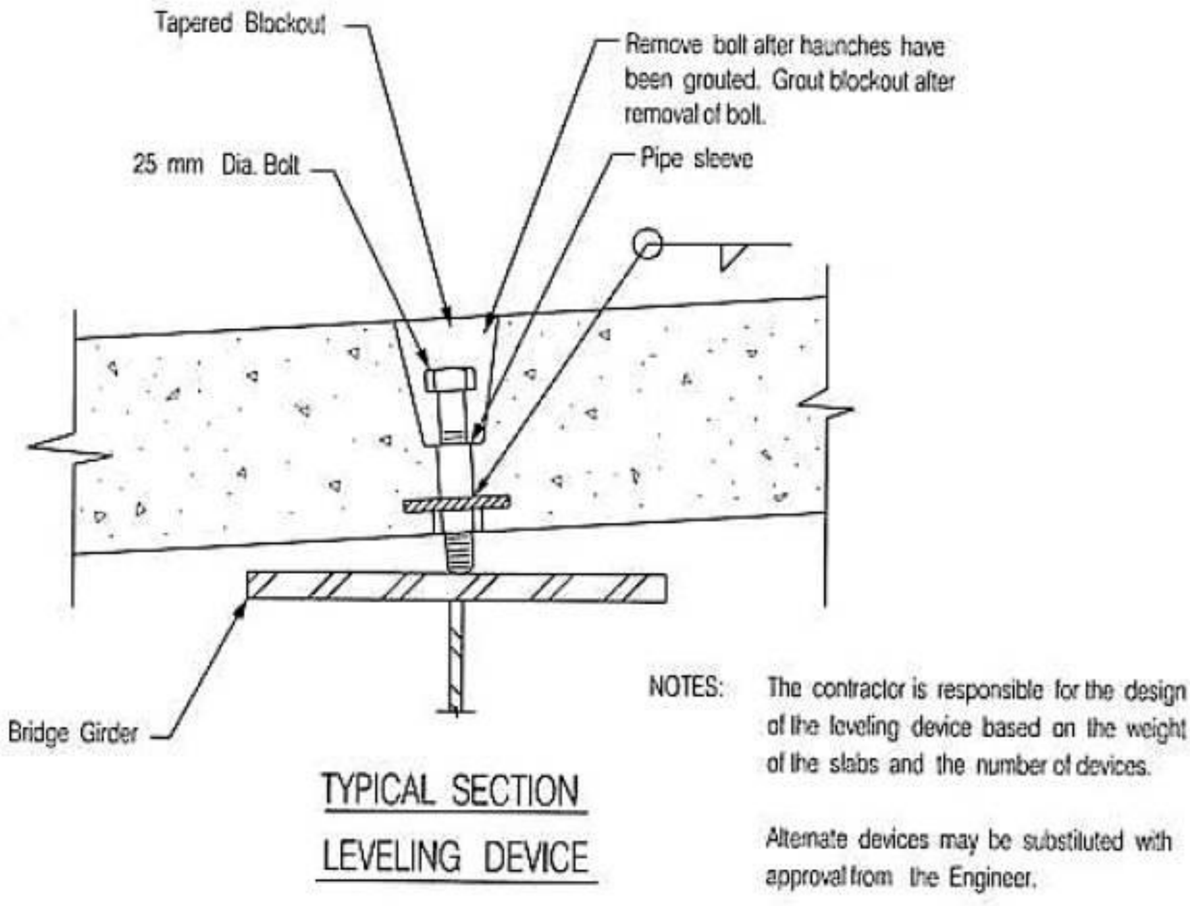


Figure 2-54: Leveling bolt [3]

2.1.5.2 Substructure element connections

Within a substructure, joints are used to connect columns, piers, or walls to a cap beam as well as to the footing [2]. While it is easy to access the connections to the pier cap beam for inspection, the connections to the footing can be covered. These connections can experience high shear and bending moment, especially from lateral loading due to the earthquake. Additionally, in the longitudinal direction, it may undergo considerable lateral loading due to high deformation from thermal expansion of the deck slab [2].

Cap beam connection to column

Precast cap beam may connect to the cast-in-place column, a precast concrete column, steel pile, or precast concrete pile. There are different methods to join the column to cap beam. The connection of column to cap beam can form in the cap beam or along the column. In another method, the cap beam can be welded to the column. A summary of different methods to connect cap beam and columns are listed in Table 2-8.

Connection inside the Cap- Grouted Sleeve: One of the merhods for connecting precast pier columns to the prefabricated pier caps is to use grouted sleeve. In this method, slots or sleeves in the cap receives the extended reinforcing bars from the column.

Connection inside the Cap- Grouted Pocket: In another method that can be used to connect precast cap beam and the cast-in-place concrete columns or steel piles and columns, a large oversized pocket in the pier cap is left to receive the column or pile. The pocket is intended to receive the longitudinal bars extended out of column (Figure 2-55) or the entire column section [5].

In this method, after installation of column or pile, the column or pile is inserted into the cap beam pocket and leveled. Then, the grout is poured from the holes on the top of the cap beam. When the pocket is used to insert the entire column section, a thin layer of grout may be used between the cap beam and column to provide a uniform bearing [39]. This method has been used by MnDOT to connect cast-in-place pile and precast cap beam, as shown in Figure 2-56. This connection also can be used to connect the pier column to pier cap integrally constructed with superstructure, integral abutments, or semi-integral abutments [2]. This technique can also be used to connect driven steel piles and precast cap beam.

Connection along the Columns- UHPC Column Segments: Another type of connection between the precast column and precast cap beam where connection is formed along the columns has been recently developed under an ABC-UTC project using UHPC at Florida International University. The details of this connection for the seismic and non-seismic region are depicted in Figure 2-57 [40]. In the proposed connection for the seismic region, two layers of UHPC is used. The second layer near the cap beam is used because of the potential for significant stresses in this area. In the none-seismic connection, the two members are joined simply with a layer of UHPC.

Connection along the Column- Grouted Sleeve: Sleeves can be left at the top end of precast or cast-in-place columns to receive reinforcing bars projected downward from the cap beam.

Welding: Another kind of connections that can be used to join column or pile and cap beam is welding. In this method, a steel plate embedded at the bottom of beam and the top of pile or column is welded to the plate [2].

Connection of Cap Beam Segments: When the width off the bridge deck is large, it is possible to have a cap with large dimension and massive weight that can make problem in shipping. In this case, the cap beam segments can be constructed with a smaller dimension. Then, the cap beam segments are connected in the field using cast-in-place closure pour method [2].

Table 2-8: Different connections of cap beam and column

Type	Connection method	Usage
Formed in cap beam	Grouted sleeve	-Connect precast cap beam to cast-in-place or precast concrete column
	Grouted pocket	-Connect precast cap beam and precast or cast-in-place concrete column -Connect precast cap beam and steel pile or column
Formed along the Columns	UHPC column segment	-Connect precast cap beam and precast concrete column
	Grouted sleeve	-Connect precast cap beam and precast concrete column
	Mechanical couplers	-Connect precast column to to cap beam
Other types	Welding	-Connect precast cap beam and steel pile or column
Cap beam segments	Closure pour	-Connect precast cap beam segments
	Mechanical couplers	-Connect precast cap beam segments to create moment connection

Figure 2-55: Column to cap beam connection using grouted sleeve method [5]

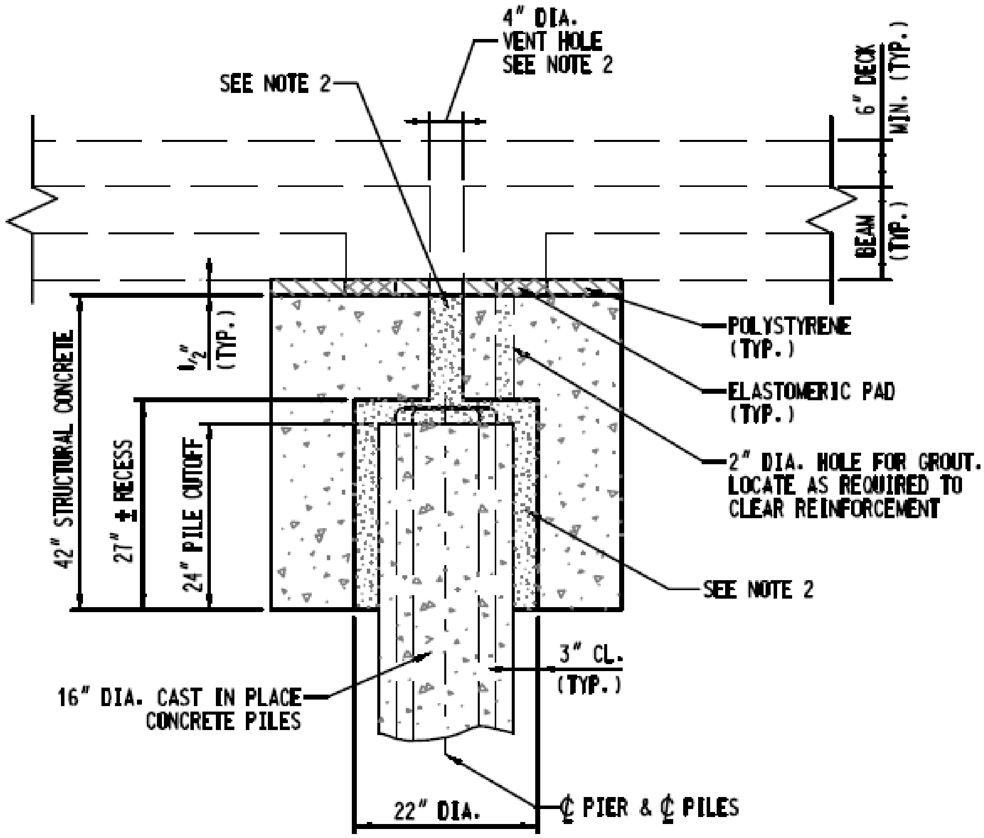


Figure 2-56: Precast cap beam and cast-in-place column using grouted pocket [2]

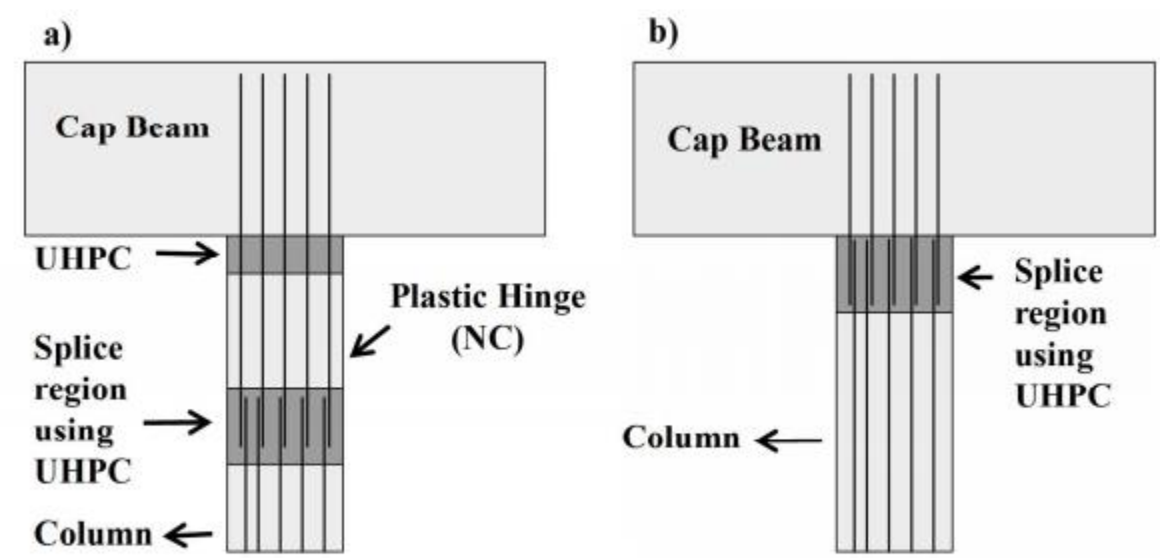


Figure 2-57: a) Seismic and b) non-seismic detail of UHPC connection of precast column and precast cap beam [40]

Footing connection to column

Another connection in the bridge substructure is the connection between column and footing. A summery of the column to footing connection is given in Table 2-9. The precast concrete column may either need to connect to the cast-in-place concrete footing or to precast concrete footing [2]. To connect the precast concrete column to the cast-in-place footing, two methods can be used.

Connection along the Column, Grouted Sleeve: In this method, the footing is cast with waiting reinforcing bars projecting from the footing. Sleeves are incorporated at the lower end of the precast column to receive the bars projecting from the footing. The column is then braced in its position on the top of the footing using temporary supports. Then the grout is poured in the sleeves around the projecting reinforcing bars. This connection is formed in the column and called grouted sleeve connection method (Figure 2-58). Utah DOT used this connection to join the precast column to precast footing.

Connection along the Column, Mechanical Couplers: In another method, the mechanical couplers can be used to connect the cast-in-place footing to the precast column. The details of the mechanical couplers used by Florida DOT are shown in Figure 2-59. When the footing is also prefabricated, the grouted sleeve or splice connection method can be used.

Connection in the Footing, Grouted Pockets: Recently, a study was conducted at the University of Nevada on the performance of the pocket connection to connect precast carbon fiber reinforced polymer column to cap beam or footing (Figure 2-60). The results showed that an insertion depth of 1.0 time the column cross section into the footing is adequate to provide a pocket connection with good seismic performance [41]. In another study, a synthesis on the behavior and performance of pocket connection in seismic regions was conducted to define a standardized pocket connection detail. The results showed that full plastic moment occurs in the column. Also, the full precast column or partially prefabricated column can be inserted into the pocket [18].

Connection between column segments: In some cases where the heights of the columns are long, column segments are prefabricated and connected to each other in the field to make the prefabricated column handling easier. To establish continuity and the required strength, the segments are post-tensioned and grouted in the field (Figure 2-61) [2]. Grouted sleeves, mechanical couplers, and other types of connection can be used between column segments.

Table 2-9: Different connections of column and footing

Type	Connection method	Usage
Formed along the column	Grouted sleeve	- Connect precast concrete column and cast-in-place footing - Connect precast column to precast footing
	Mechanical couplers	- Connect cast-in-place footing and precast column
Formed in footing	Grouted Pocket	- Connect precast column and precast or cast-in-place footing
Column segments connection	Closure pour Grouted sleeves mechanical couplers	-Connect precast column segments

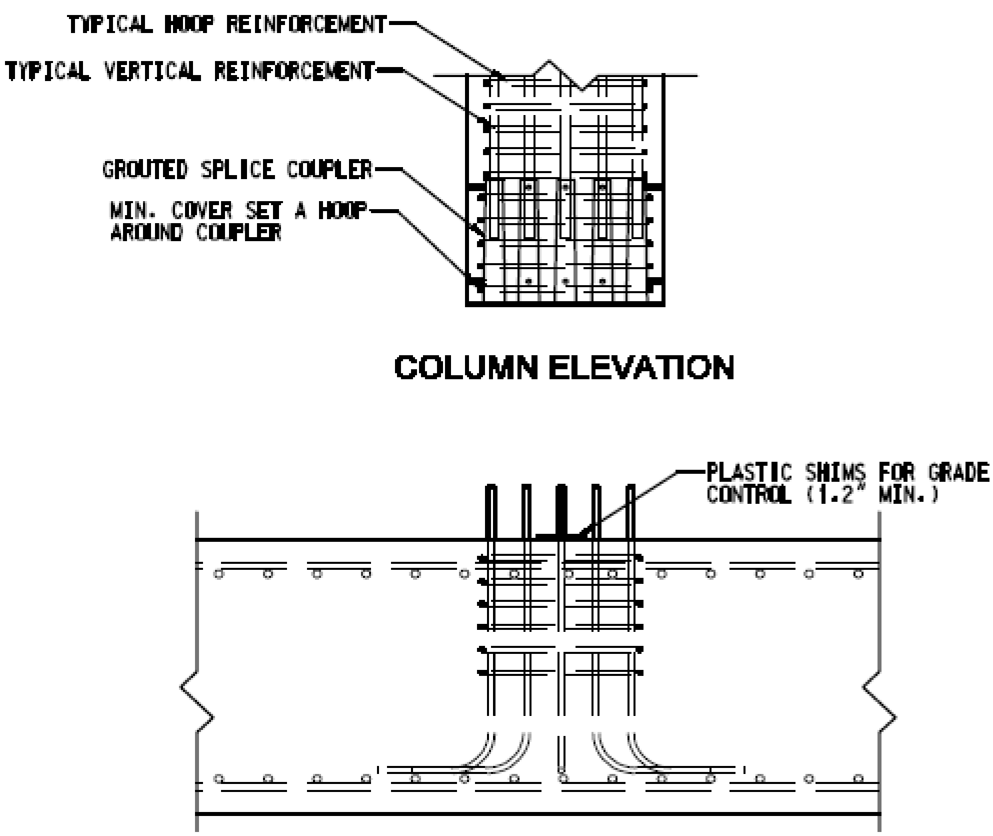


Figure 2-58: Grouted sleeve connection between footing and column [2]

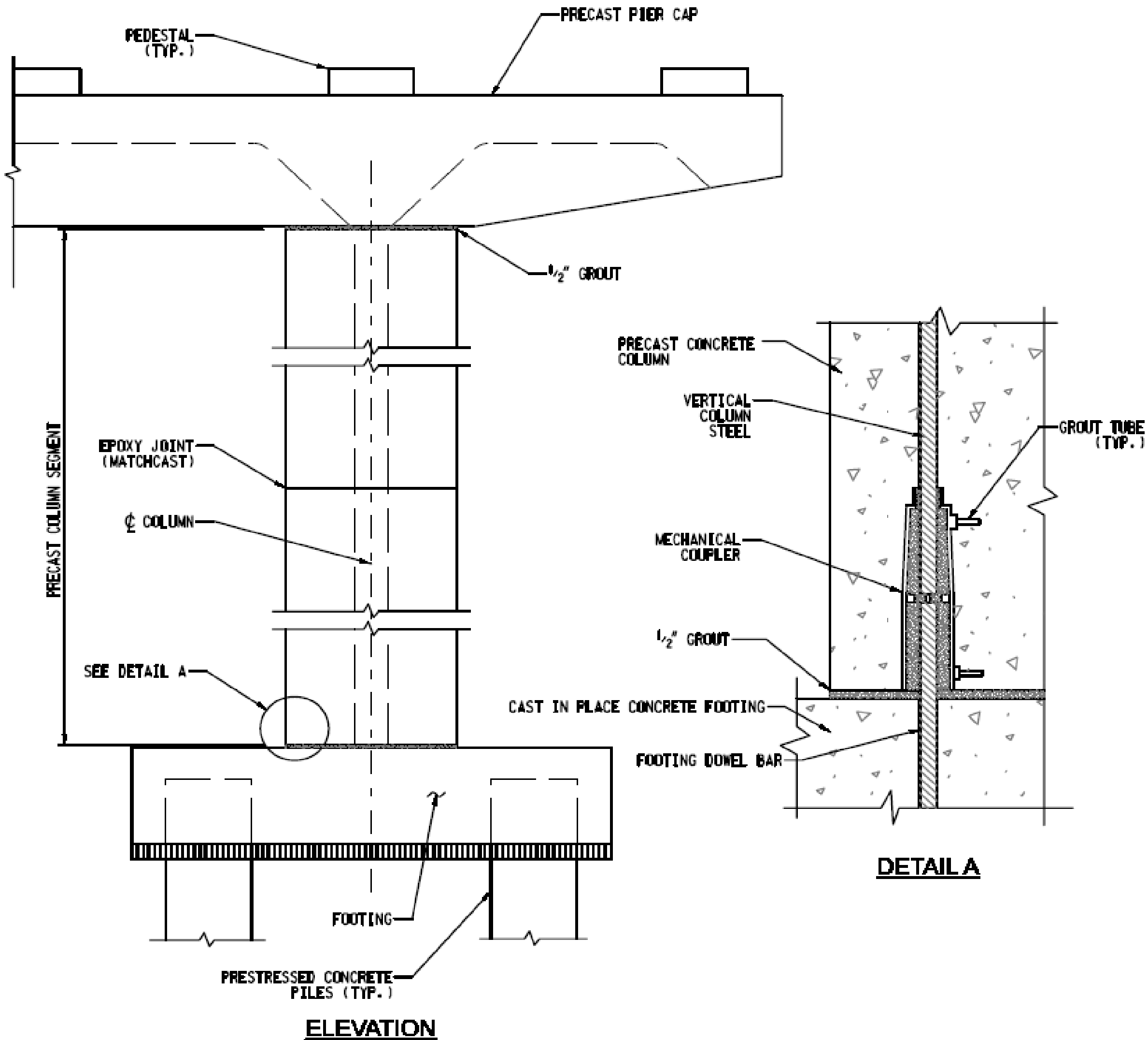


Figure 2-59: Cast-in-place footing to precast column connection using mechanical couplers [2]

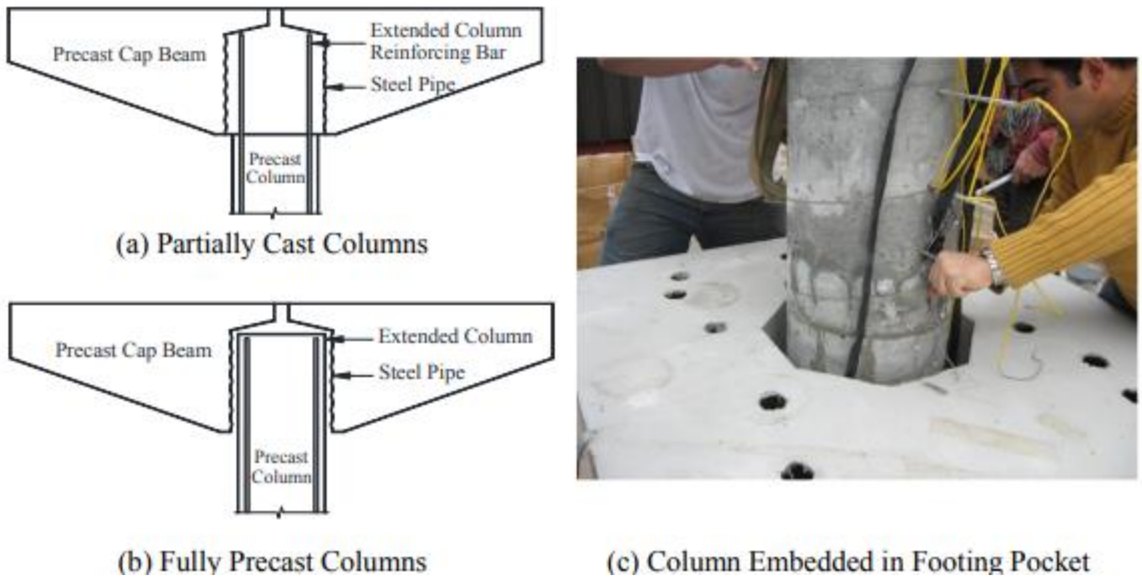


Figure 2-60: Pocket connection of footing and column [18]

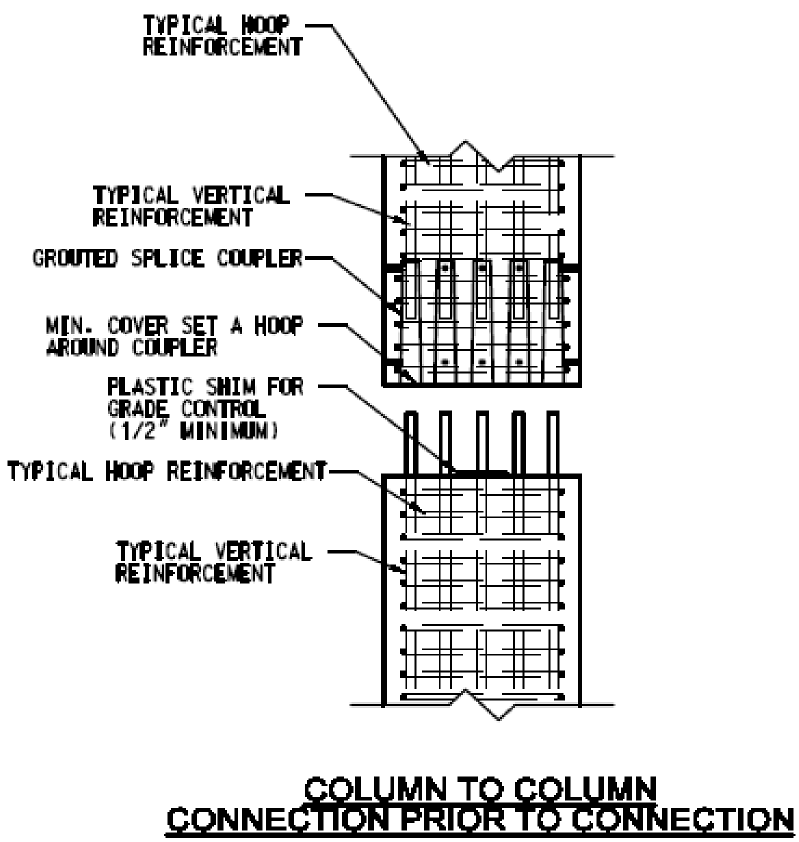


Figure 2-61: Column to column connection [2]

Abutment and wall systems connections

Abutment systems including cantilever abutment, spill-through abutment, precast wall, integral and semi-integral abutments are other components of the bridge that can be constructed off-site and connected to each other in the field. The connections that can be used to join the abutment components together are summarized in Table 2-10.

Closure pour: Cast-in-place closure pour is the connection method that can be used to connect the integral abutments elements and join abutment to superstructure. The disadvantage of this method is its high cost due to use of high performance concrete as a closure pour. Figure 2-62 depict this connection details [42].

Grouted Sleeve/Splice couplers: Grouted splice couplers can be used to connect precast elements like abutment stem and footing [2]. This connection type has been used by New Hampshire DOT to connect all of the abutment elements and is shown in Figure 2-63. In the cantilever abutment system, the connection of backwall to abutment stem is also needed (Figure 2-64, 2-65). Backwall is used to support the soil behind the beam ends. To connect backwall to abutment stem, the grouted splice couplers connection, same as abutment stem to footing connection, can be used. Also, other types of connections based on the conditions can be used. Another connection in the cantilever system is precast breastwall (checkwall) to abutment stem. Breastwall in this system is used as a decorative element at the corner of the abutment to connect the end of the beams. To attach precast breastwall to abutment stem, grouted splice couplers or other kind of connections based on the conditions can be used. In another type of abutment system, spill-through abutment, the same type of connections as that used for cantilever abutment can be used [2]. Other connecting methods of the precast wall to the precast footing include grouted shear key and using mechanical connectors. Recently, a study conducted by Iowa State University evaluated durability, strength, and application of grouted couplers in the integral abutments. The grouted reinforcing bar and pile couplers were evaluated, and this connection detail was established [17, 42].

Grouted Pocket Connection: In some cases, the abutment stem or cap connect directly to steel piles or precast concrete piles. One way to establish this connection is by embedding piles into prefabricated pockets in the abutment stem and grouting the space between (Figure 2-66, 2-67).

*Welded Plate Co*nnection: To connect the steel piles directly to abutment, steel plates can be anchored in the abutment, and welded to the piles.

Steel bar dowels connection: To make the abutment integral with the superstructure, steel bar dowels can be used between the abutment stem and abutment cap that is made integral with the superstructure. Figure 2-68 shows a dowel connection.

Small closure pour: In some cases, because of the abutment dimensions and shipping limitations, the abutment cap may be prefabricated in segments [2]. These segments can be attached to each other in the field. To connect them, the match cast and post-tensioning method which is used by Maine DOT or a small closure pour technique can be used (Figure 2-69).

Table 2-10: Abutment systems connections

Connection type	Connects
Closure pour, grouted pockets or sleeves	-Abutment elements -Abutment to superstructure
Grouted Sleeve/Splice couplers	-All types of abutment elements
Grouted Pocket Connection	-Abutment stem or cap directly to steel piles or precast concrete piles
Welded Plate Connection	-Steel piles to abutment
Steel bar dowels connection	-Pile cap and integral abutment
Small closure pour	-Abutment segments to each other
Simple grouted shear key	-Abutment cap segments

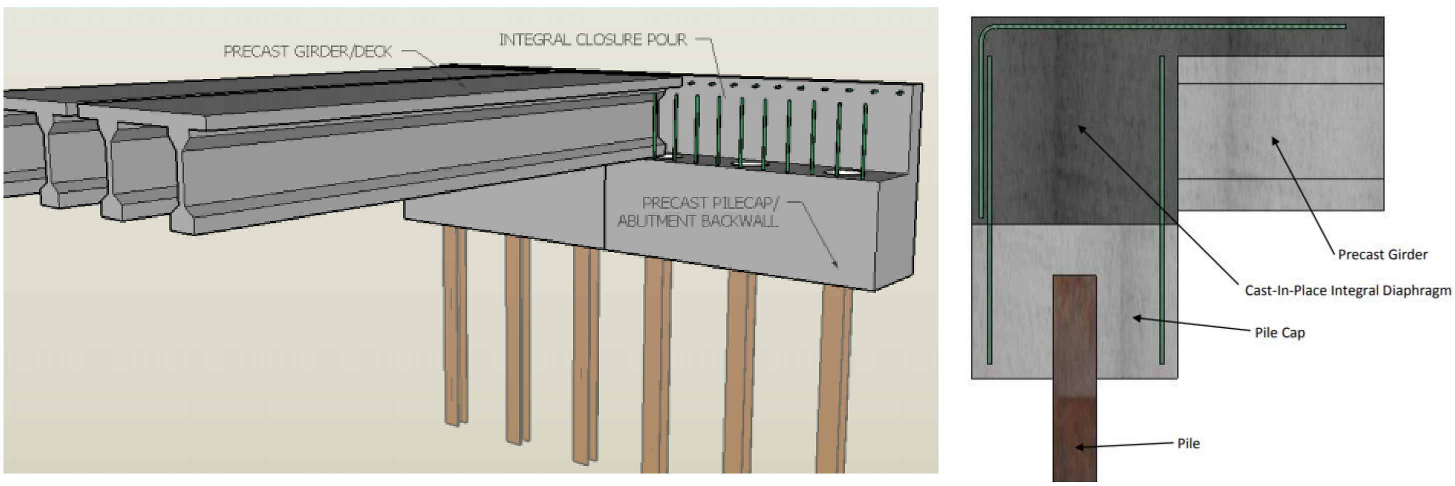


Figure 2-62: Closure pour connection in abutment [42]

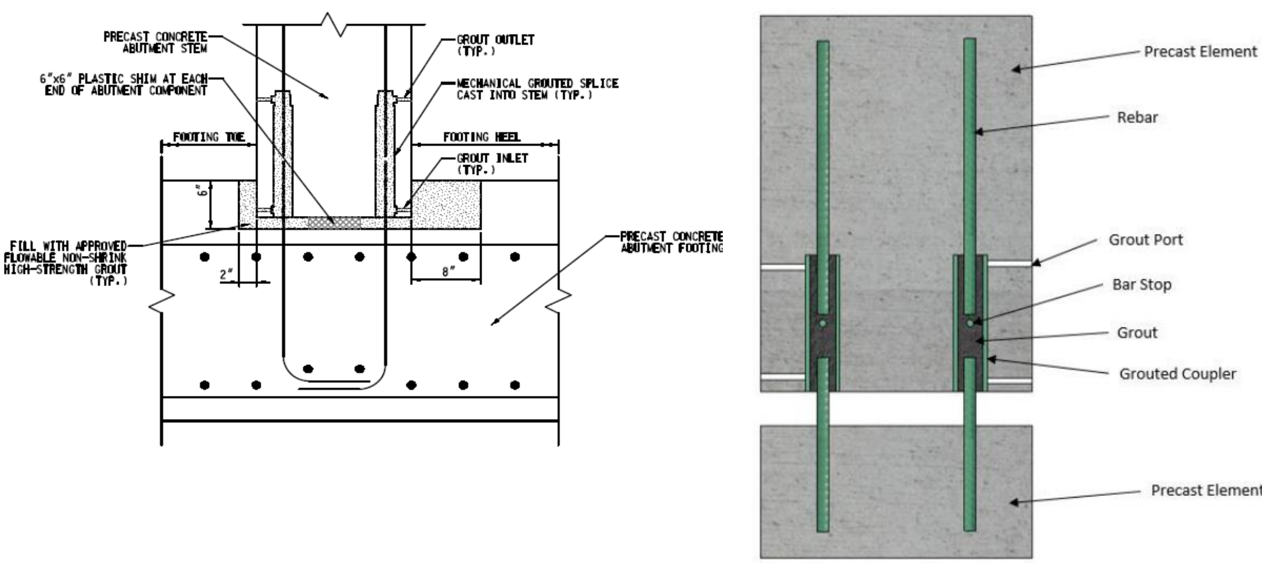


Figure 2-63: Precast abutment stem to precast footing connection [2, 42]

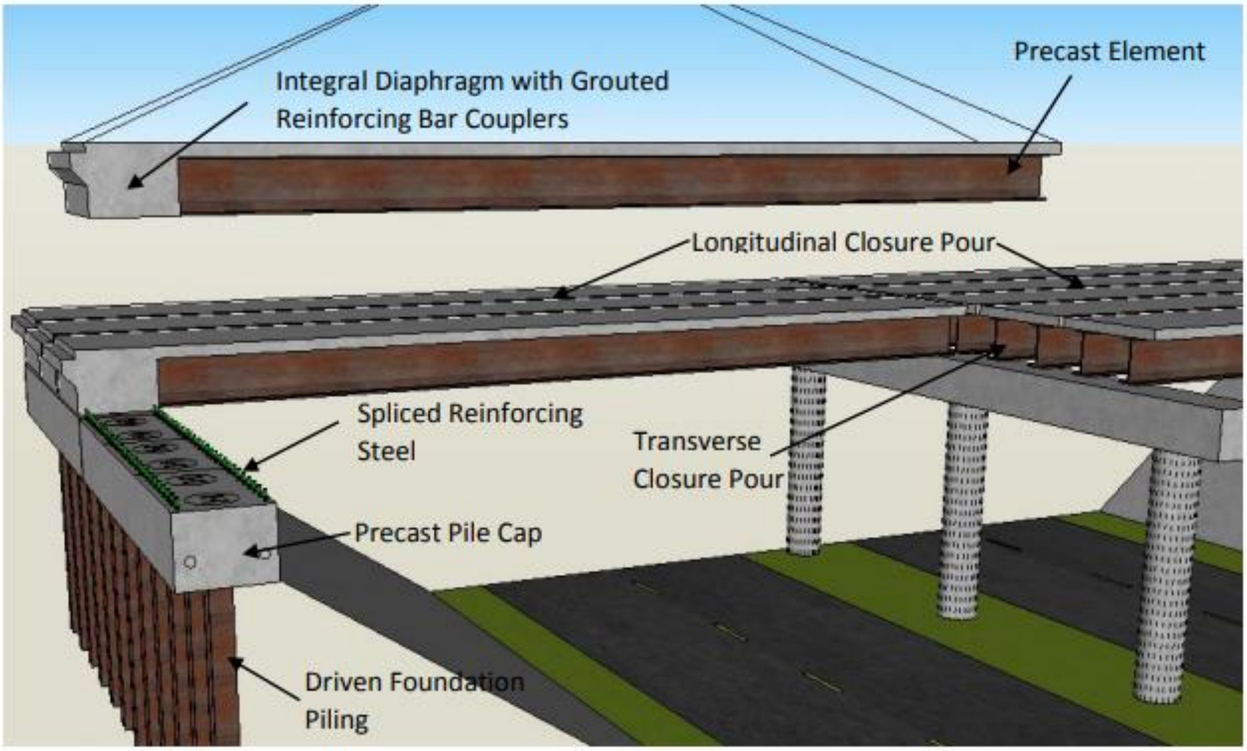


Figure 2-64: Grouted couplers connection in prefabricated abutment [42]

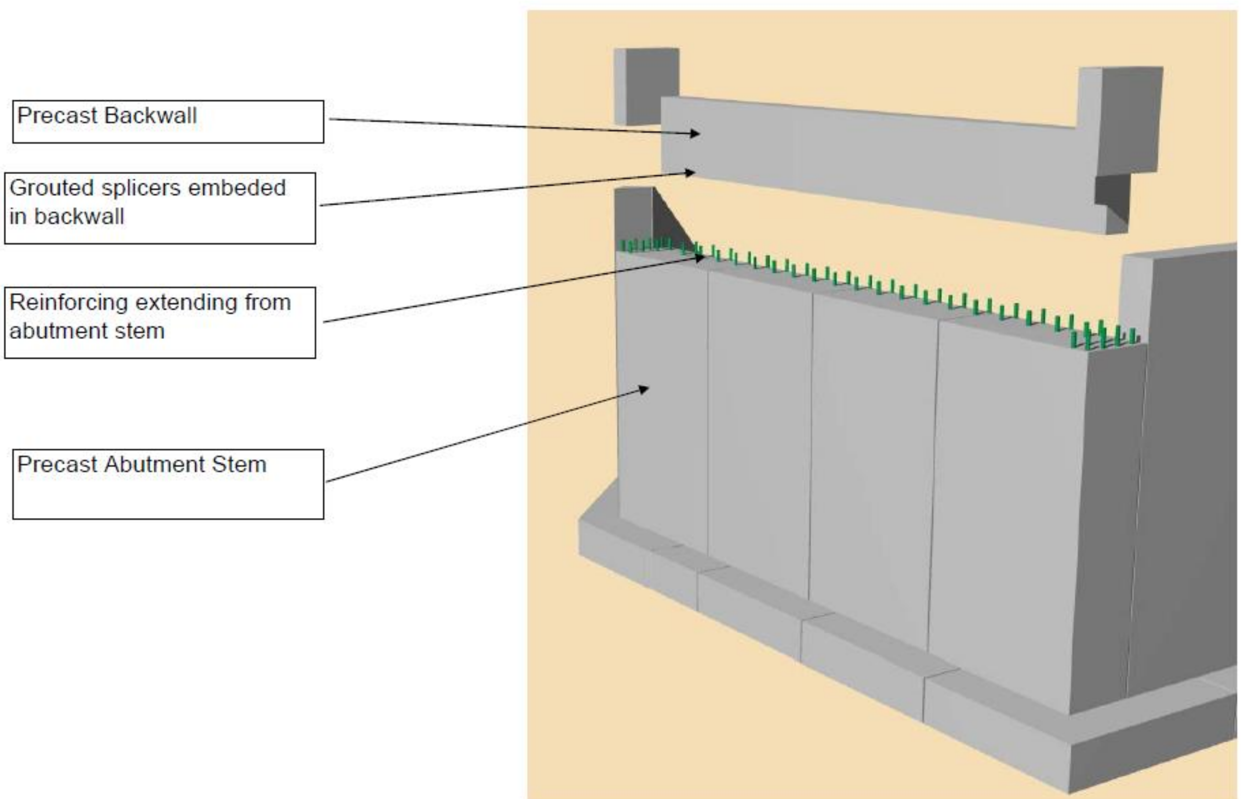


Figure 2-65: Abutment connection [2]

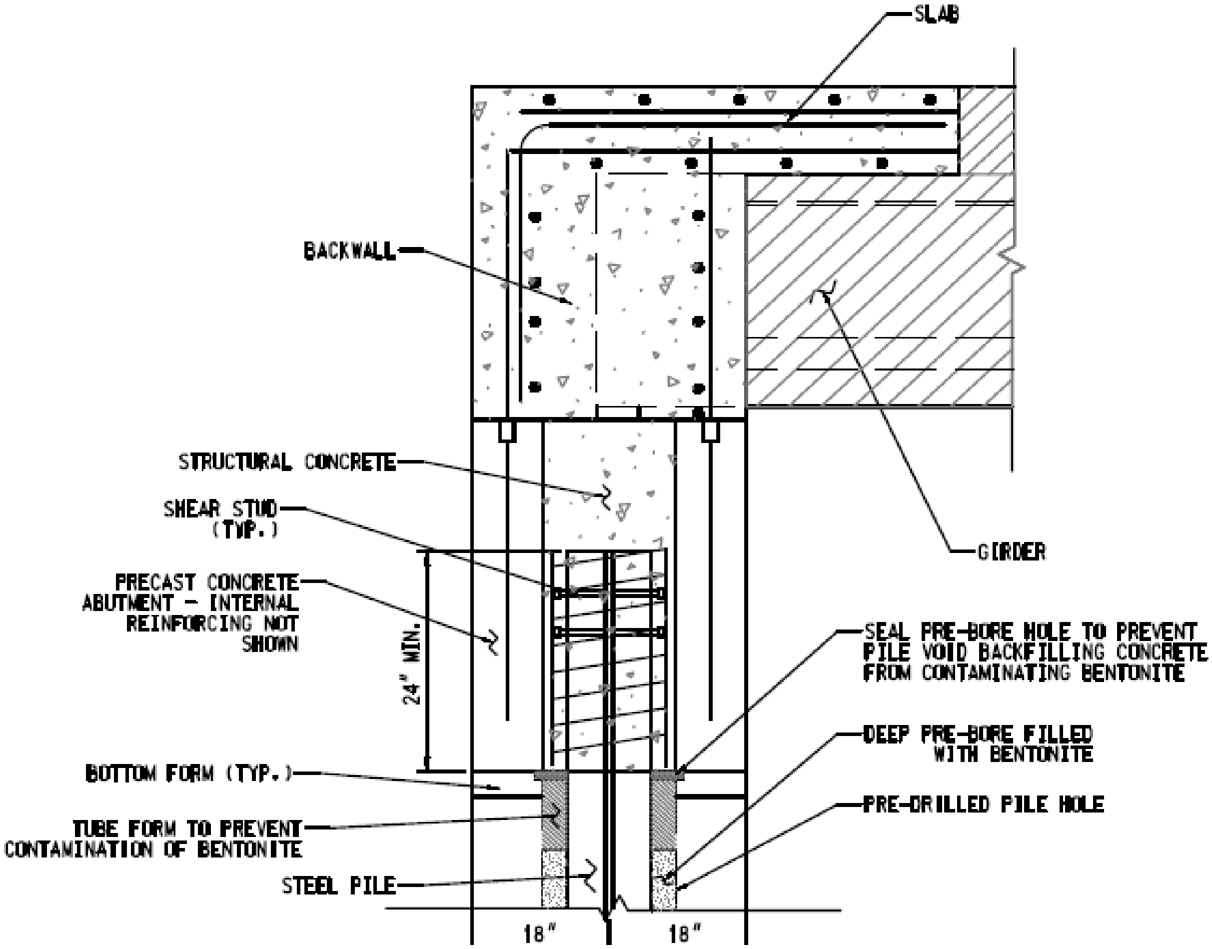


Figure 2-66: Precast integral abutment connection to steel pile [2]

Figure 2-67: Precast integral abutment connection to steel pile [2]

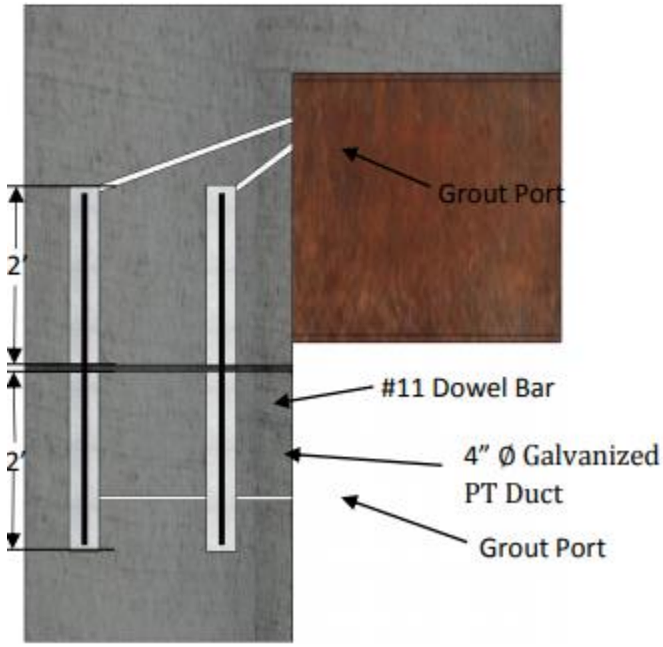


Figure 2-68: Steel bar dowels connection in abutment

Figure 2-69: Adjacent abutment segments connection [2]

2.1.5.3 Foundation connections

Proper connections are required between different precast foundation elements to successfully transfer the load to subgrade soil and resist failure. Connections are required to ensure sufficient joints between precast footing to steel and concrete pile, precast footing to precast footing and precast box cofferdams. Details of different connections in foundation systems are discussed in the following sections. Table 2.11 presents a summary of the available connections used for bridge foundation system.

Footing and Pile Systems: Prefabricated piles are most commonly used for bridges by state DOTs whereas the concept of prefabricated footings is comparatively new. The connection between the footing and pile system is important to transfer the load successfully.

Precast Footing to Subgrade Connections: The primary problem with the use of precast concrete footing is to properly seat the footing on the subgrade. Settlement or rocking of the foundation may result from inadequate seating on the subgrade. It can be eliminated by placing a flowable concrete or grout under the footing or by using leveling bolts on the corners to lift the footing above the subgrade. In such cases, low grade concrete or flowable fill can be used as this is not a structural element. A sub-footing can also be used to create a level area for footings construction in bedrock [2]. Figure 2.70 presents the connections between precast footing and subgrade materials.

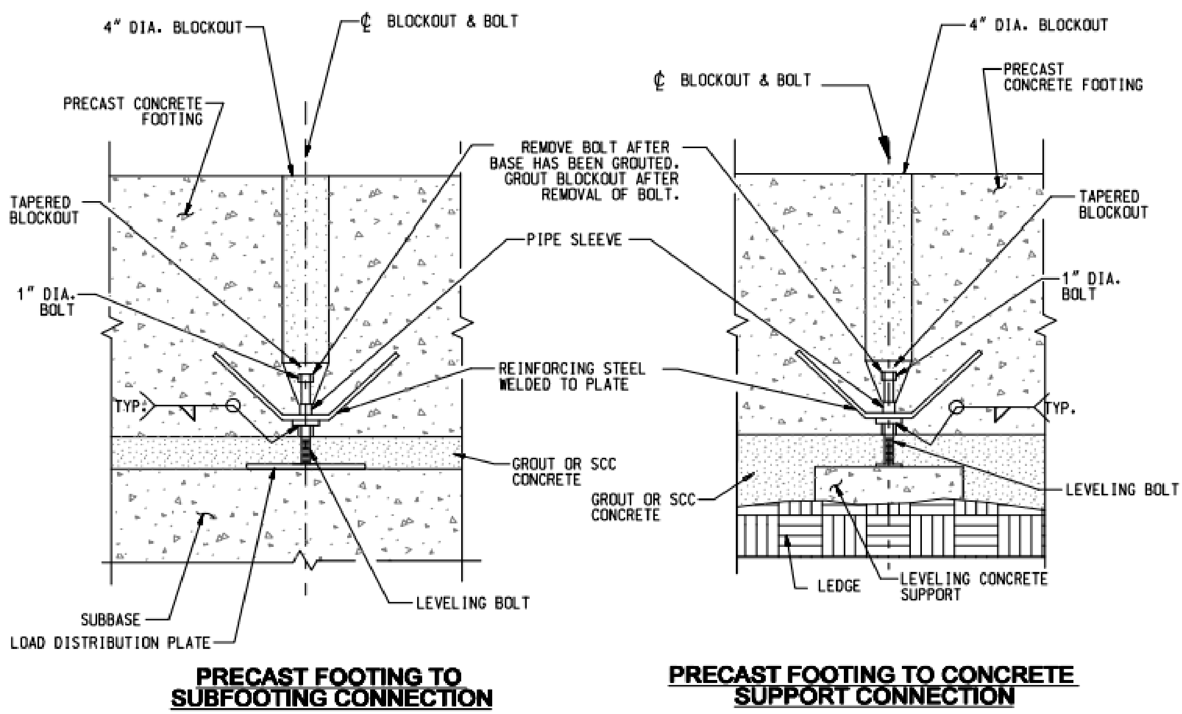


Figure 2-70 Details of Precast footing to subgrade Connection [2]

Precast Footing to Precast Footing Connections: The connection between adjacent footings elements may or may not need to be a structural connection, depending on the design. A simple grouted shear key can be used if there is no structural requirement for the connection. However, a small closure pour connection can be used if a moment connection is required (Figure 2.71). For this purpose, reinforcing steels are extended from footing elements and grout is poured in the formed area created by the two footing elements and the subgrade [2]. Figure 2.72 presents a photograph of installation of a precast concrete footing with grouted shear connection on concrete sub-footing.

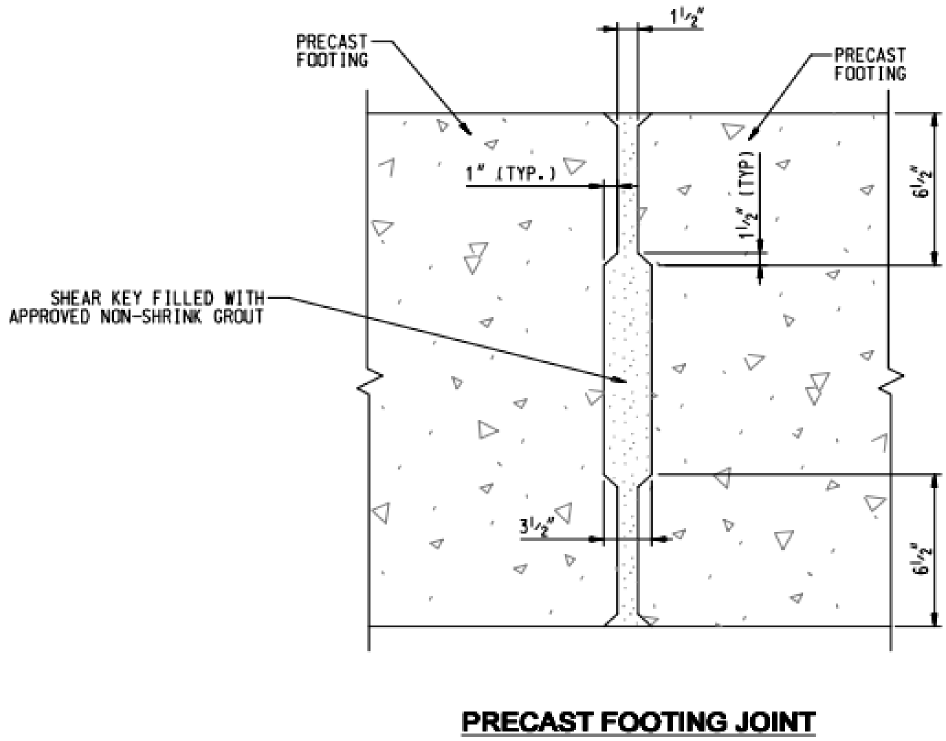


Figure 2-71 Precast concrete footing to precast concrete footing connection [2]

Figure 2-72 Installation of a precast concrete footing with grouted shear connection on concrete sub-footing [2]

Precast Footing to Steel Pile Connection: The connection details for precast concrete pier caps to steel pile mentioned in Section 2.5.1.2 can be used for precast footing to steel pile connections. However, uplift on the piles or moment capacity requirement may create problems for such connections. The pile end reinforcing steel can be welded and embedded in a closure pour to provide enough uplift capacity for this connection (Figure 2.73). Also, embedment of the pile top by at least 12 inches into the footing will help to achieve adequate moment capacity for this connection [2].

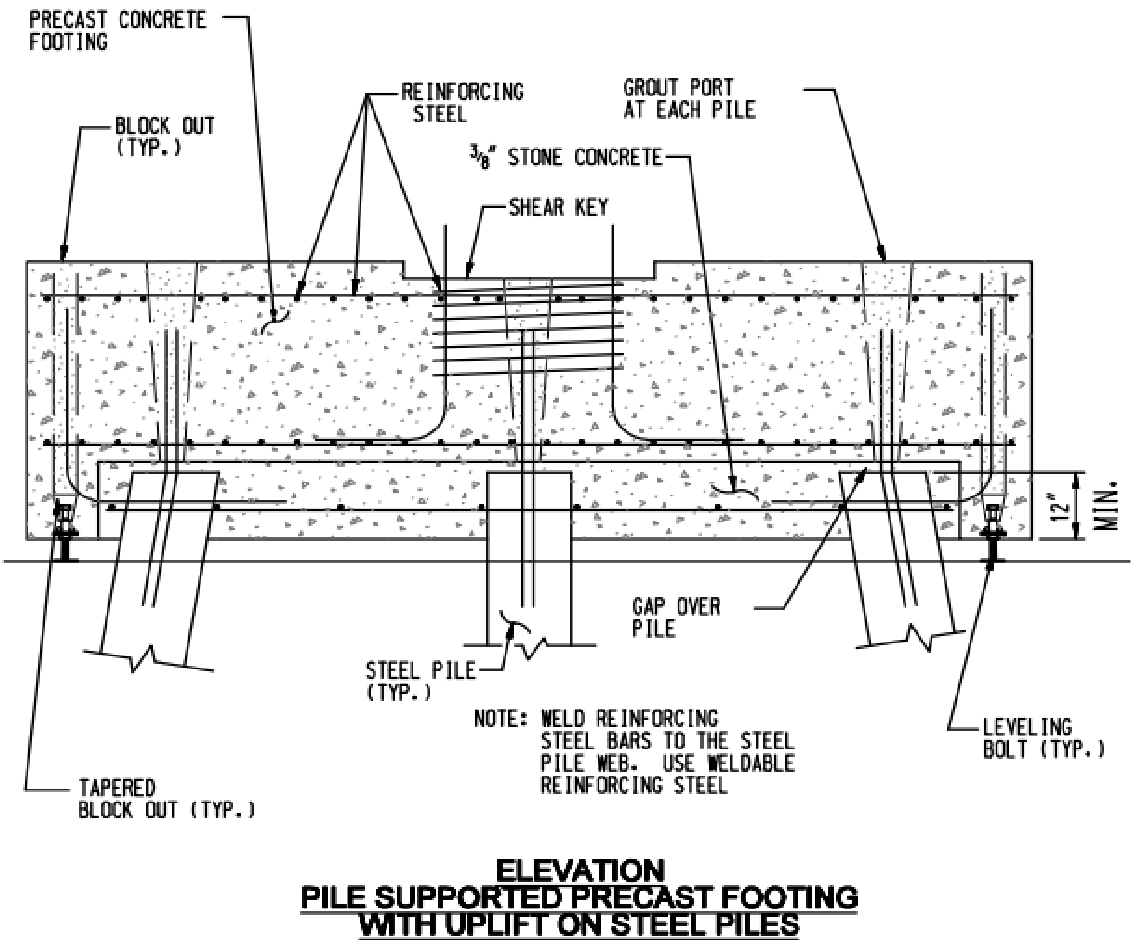


Figure 2-73 Connection between precast concrete footing and steel pile with uplift

Precast Footing to Precast Concrete Piles: Similar to steel pile connections, several states have developed connection details for precast concrete piles connected to precast concrete pier bents. There have also been concrete pile connection details developed for integral abutment bridges. For example, Florida DOT has developed a connection for a hollow precast concrete pile to a precast footing to develop full moment capacity of the pile (Figure 2.74). The connection consists of a large blockout in the footing where a reinforcing steel cage is installed between the pile top and the blockout [2].

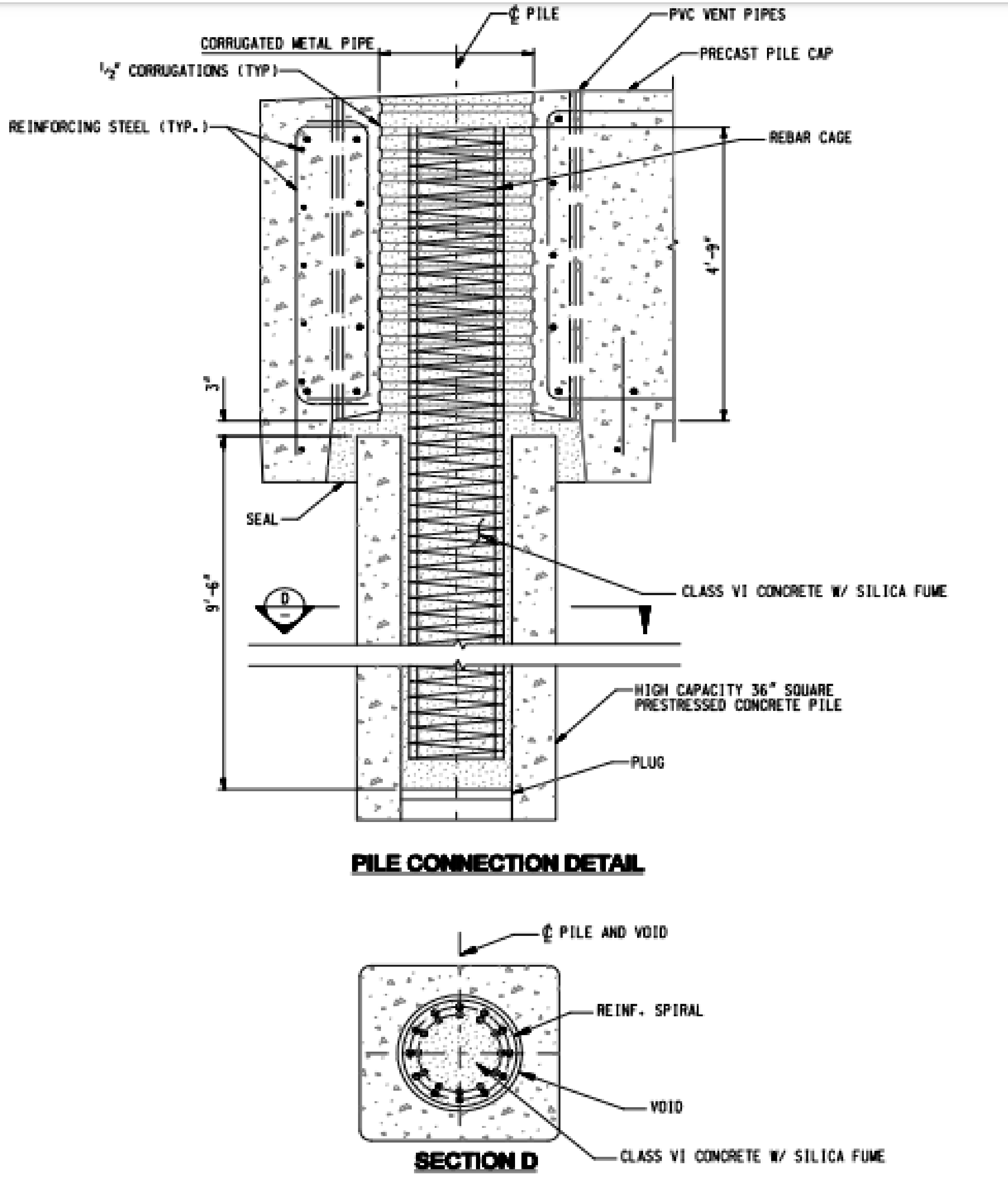


Figure 2-74 Connection details between concrete square pile and pile cap [2]

Precast Footing to Cast-in-place Pile or Drilled Shaft Connections: Till now, no connections between precast footing to cast-in-place piles or drilled shafts connected to precast concrete footings have been developed by any state DOTs. However, the precast footing to concrete pile connection details could be adapted for use with cast-in-place concrete piles or drilled shafts.

Precast Pile to Precast Pile Connection: To accommodate variations in subsurface conditions, pile lengths for some pile types can be easily adjusted and spliced in the field. Many state DOTs have developed standard details for connecting precast driven piles that need to be spliced. Precast concrete pile industry has developed standard pile splicing details [43]. The Florida DOT has developed a detail for splicing hollow square prestressed concrete piles (Figure 2.75). These details consist of a reinforced concrete closure pour between pile elements.

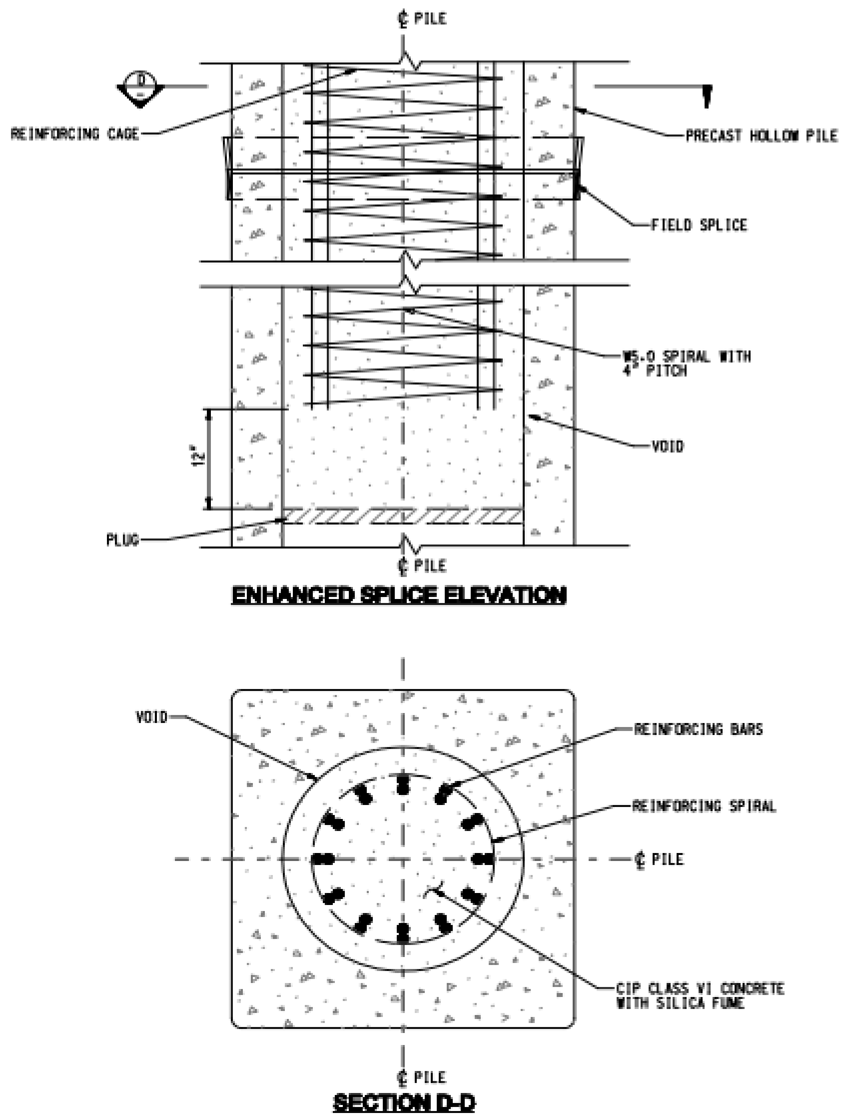


Figure 2-75 Connection between concrete square piles using splice

*Precast Pier Box Cofferdams: C*onstruction of the pier footings on piles is one of the biggest challenges during construction of piers over water. Precast concrete pier box is used to dewater the area where the drilled shaft connects to the bridge footing. Figure 2.76 presents a photograph of the new Providence River Bridge in Providence, Rhode Island where precast concrete pier boxes were hung from the 8-foot diameter drilled shafts to create dry space. The connection between the precast box and the drilled shaft was sealed with a small tremie pour around the drilled shaft.

Figure 2-76 Footing Reinforcing Placement in Providence River Bridge Pier Box

2.1.5.4 Categorizing the bridge connections according to their seismic performance

Connections can also be classified in ABC bridges into three different types based on the seismic performance and capacity of the connections, as follows (Figure 2-77 and 2-78).

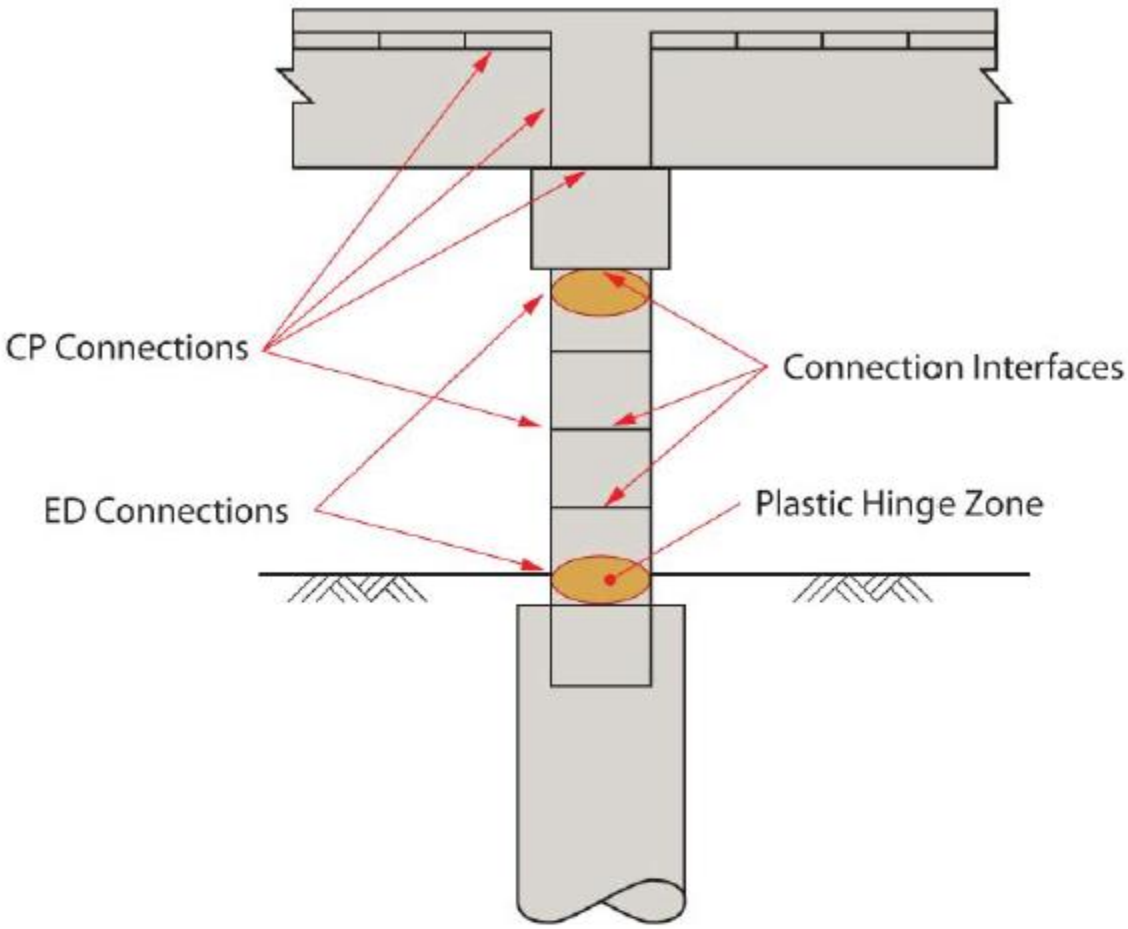


Figure 2-77: Connection locations based on prefabricated members plastic hinge zone [35]

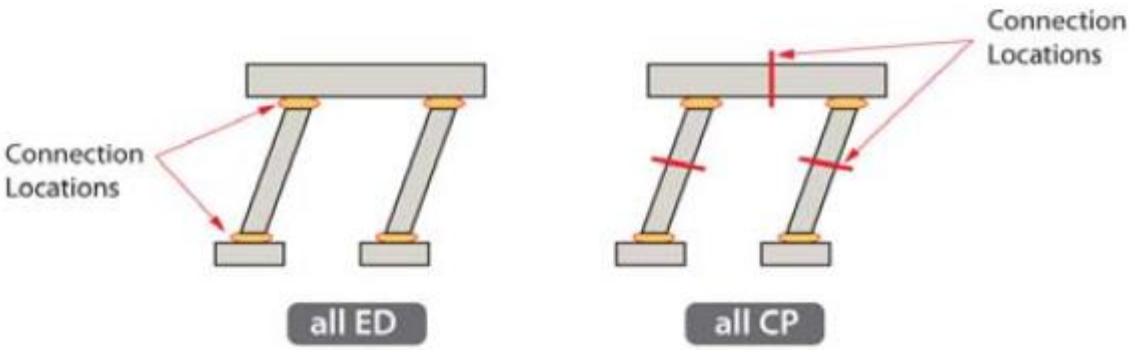


Figure 2-78: Connection locations based on their seismic performance [35]

- Capacity-protected (CP) connection: This kind of connection has a cyclic strength higher than the strength of the members that are connected. In this case, the inelastic deformation occurs in the members that are connected.

- Energy Dissipating (ED): This type of connection has a lower cyclic strength than that of adjacent members that are connecting. Therefore, the inelastic deformation can occur in the connection. This kind of connection, however, has a high ductility to dissipate kinematic energy.
- Deformation Element (DE): This type of connection cannot dissipate energy. Also, this connection has no strength in the direction that deformation occurs. It provides internal articulation between connected elements like the joint between superstructure and substructure.

2.2 Construction methods

One important and basic aspect of ABC is the use of Prefabricated Elements and Systems (PFES). Another aspect of ABC is using innovative structural placement and construction methods to improve safety, quality, and reduce the construction time. The following methods are commonly used to place bridge components or the entire bridge at the site [2].

- Self-Propelled Modular Transporters (SPMT): The SPMTs is a vehicle that is used to carry, lift, and place heavy loads like bridge elements with the walking speed and capability of maneuvering in 360 degrees [1]. There are transporters with various capacity, width, and length. The capacity of carriers is usually between 50,000 to 75,000 pounds per axle. The installation time of bridge using this transporter depends on the carrying distance, and it is generally between 2 to 8 hours (Figure 2-79, 2-80).
- Longitudinal launching: The longitudinal launching is a construction method that normally is used when the bridge is inaccessible by the crane [1]. The bridge can be constructed in a launching pit or transferred to launching pit using SPMT. Launching pit is located behind the abutment at the end or beginning of the bridge. The bridge is jacked out horizontally over the abutment to be installed in position (Figure 2-81).
- Horizontal skidding or sliding: The horizontal skidding or sliding known as lateral sliding is an ABC method [1]. In this method, the superstructure is constructed parallel to the bridge placement location on the temporary supports. The temporary supports are located over the rails. To place the superstructure, the hydraulic system or cables are used to move the superstructure transversely. This method also can be used to slide the superstructure to the existing bridge after demolishing the existing superstructure (Figure 2-82). This allows the old bridge to function until shortly before the sliding.
- Other heavy lifting equipment and method: There are several other equipment and techniques to lift the bridge [1]. One approach uses a strand jack or climbing jack (Figure 2-83). Strand jack pulls up the bridge and climbing jack pushes up the bridge. In this case, the bridge is constructed at the ground, and then lifted up using strand jack or climbing jack. The bridge is transferred to the location for lifting by SPMTs method and barges. Another technique is transverse pivoting which can rotate the bridge to its location precisely (Figure 2-84). Also, transverse gantry crane or longitudinal gantry crane can be used to place the bridge (Figure 2-85, 2-86).

- Conventional cranes: The conventional crane can be used to install and place the prefabricated bridge elements including footings, pier columns, pier cap, girders, and deck panels (Figure 2-87) [1].

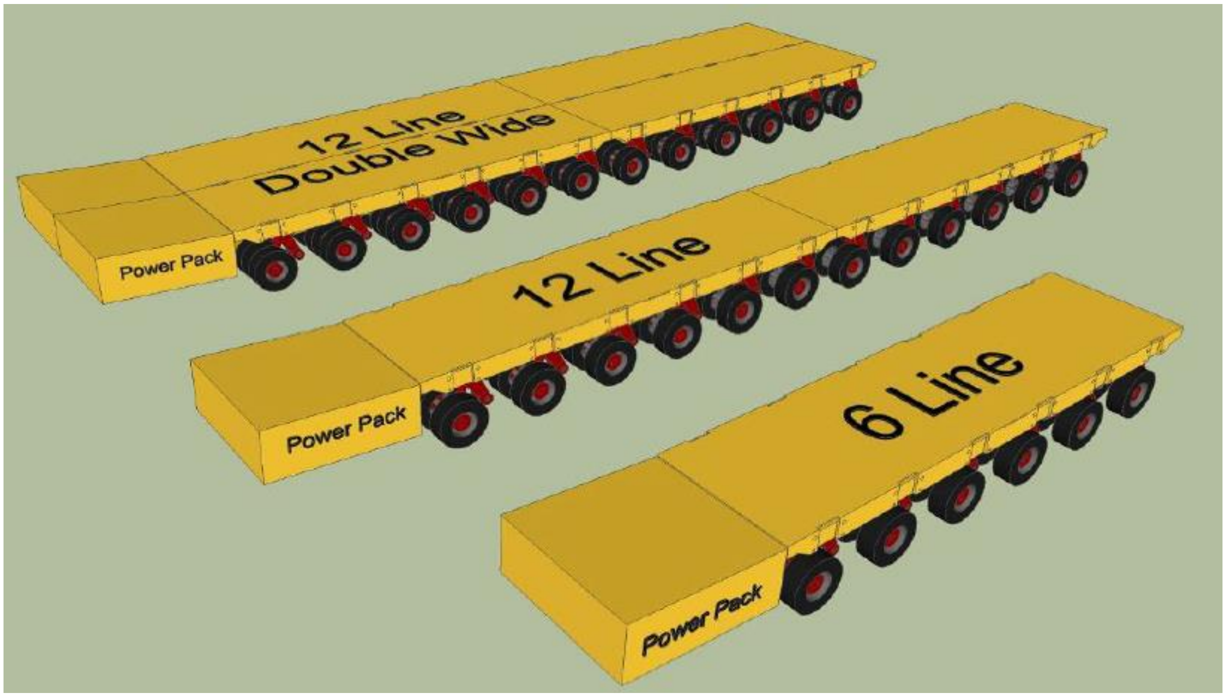


Figure 2-79: SPMTs configuration [1]

Figure 2-80: SPMTs bridge move [1]

Figure 2-81: Longitudinal launching construction method [1]

Figure 2-82: Lateral bridge sliding [1]

Figure 2-83: Jack lifting of the bridge [1]

Figure 2-84: Vertical axis pivot [1]

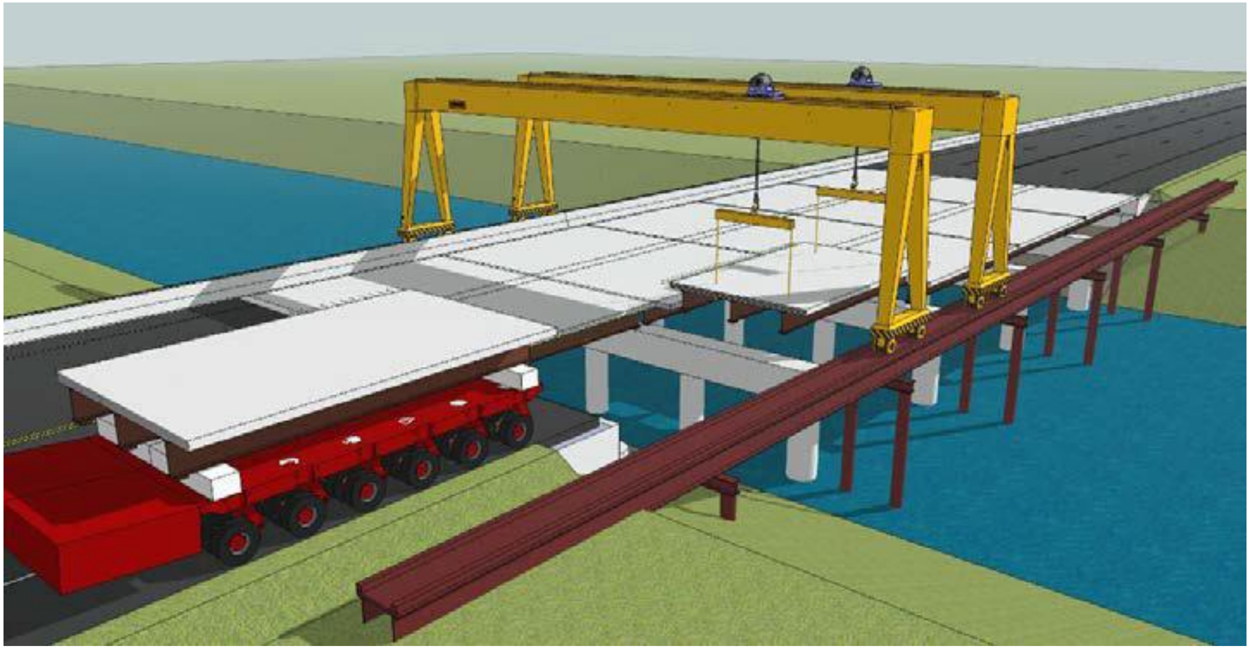


Figure 2-85: Transverse gantry bridge placement [1]

Figure 2-86: Longitudinal gantry bridge placement [1]

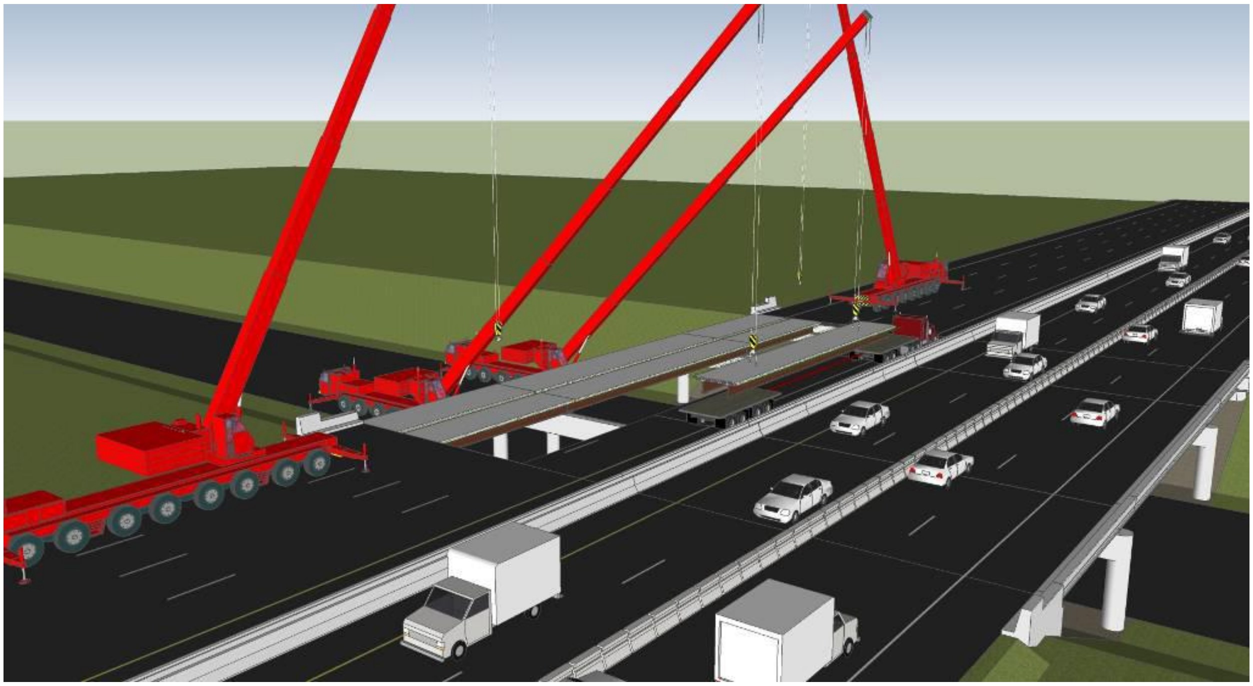


Figure 2-87: Bridge placement using conventional cranes

2.3 Potential Issues with Design and Construction

At a minimum, the bridge design and construction should emulate the conventional bridge construction and design [2]. To design the ABC elements, the AASHTO LRFD structural specification design should be followed. The design and analysis of ABC connections are also according to the AASHTO specification design for mechanical reinforcing devices. It requires that the device resist 125% of yield strength of the reinforcing bar [44]. However, the AASHTO specification does not cover all the aspects of ABC design and construction. Another critical issue in ABC is lifting and moving of large-scale elements. In this case, the location of supports and stiffness of supports used in moving and lifting of elements in the prefabricated elements should be defined. However, the AASHTO specification does not cover this issue. Utah DOT studied the effect of dynamic load due to movement of prefabricated elements. Although that study was limited, it was concluded that the dead load of members should be considered 15% more than their actual weight due to the effect of the dynamic load from elements movement [2]. According to a survey, the most common concern of states is lack of standard in the construction and design of ABC bridges [45], the high cost of ABC, inexperienced contractors, and staging of ABC elements. Exceptions also exist. The Hawaii DOT demonstrated that ABC has a lower cost than cast-in-place projects. Also, there is ongoing research to define the total construction cost of ABC including users cost and long-term maintenance costs [46]. The issues in the construction and design of ABC elements and connections are summarized below.

Another issue that needs to be addressed is related to the structural analysis method of the bridge. It is critical to determine if there is any changes in the type of analysis method and load distribution of the structure because of or as a consequence of implementing method of accelerated bridge construction. This issue should be considered for different prefabricated elements and configuration. Also, the loads associated with the lifting and supporting point of prefabricated elements during their erection including dynamic effects should be defined [47].

2.3.1 Superstructure

New Mexico DOT used the full depth precast deck in a project. The problem that DOT encountered was that fabricators, contractors, and designers did not have enough experience. Due to this problem, the fabrication, designing, and placement of the project took very long [45]. There is an ongoing research about the performance of full-depth precast deck concrete to address the full-depth deck construction concerns [48]. In this study, the actual in-service performance of full-depth precast panel will be compared to the cast-in-place deck method in addition to provide a successful construction detail for this member.

2.3.2 Substructure

According to a survey, pier cap durability and behavior in seismic condition is one of the crucial issues that has limited the use of ABC. California DOT described this issue as the one needs to be addressed [45]. TX-DOT assessed different connections of grout pocket, grouted vertical ducts, grouted sleeve couplers, and bolted connections that can be used for the cap beams [49]. Nevertheless, the performance of these connections was not investigated in the seismic regions. Therefore, use of these connections in seismic areas needs to be investigated. Moreover, the sufficient tolerance of cap beam duct and its diameter is one of the primary concerns in the placement of cap beam [49]. Another issue mentioned in the study was the durability of grout that is poured in the pockets. The grout should have sulfate and freeze-thaw resistance.

2.3.3 Foundation

Selection of proper foundation is always a challenge for bridge structure. It was found that some states often select deep foundation even though spread footings are technically feasible and cost effective [50]. However, Virginia DOT suggested not to use deep foundations indiscriminately for all subsurface conditions [24]. A survey conducted by Georgia Southern University indicate that few DOTs are reluctant to use precast footings because of concerns about connection durability [45]. Therefore, more research is needed for designing durable connections between precast footing elements. Also, concerns about the quality control and quality assurance as well as pile integrity of CFA piles limit their' use [27]. Some other challenges in foundation construction are retention of excavated earth, construction in deep water, etc. [1].

2.3.4 Joints and Connections

One type of joint used for connecting columns to the footing or connect the column to pier cap is mechanical reinforcing splice or couplers (splice couplers connection method). AASHTO structural specification does not allow the use of this connection in the plastic hinge zone of the column in seismic regions. However, the ACI building code allows the use of this connection in seismic areas. Therefore, this connection needs more research so that it can be permitted by AASHTO for use in seismic regions [35].

Corrugated voids in the prefabricated elements are used to connect the elements to each other. These voids can reduce the weight of elements during shipping and transfer shear and moment between connected elements. AASHTO specification does not define the required cover for this connection. This question needs some more research to define the required cover in the construction of prefabricated elements in different conditions [1].

A survey was conducted by Georgia Southern University about the implementation of ABC and the issues encountered by state DOTs [45]. In that survey, most of the state DOTs had concern about the durability and long-term performance of UHPC closure pours. There is ongoing research at ABC-UTC to study the long-term corrosion protection provided by UHPC used in joints and substructure elements [51].

3 New Bridge Construction

The particular concept in the use of ABC method and prefabricated elements in the construction of bridges is considering time equivalent to money. The main mission of the ABC and the use of prefabricated elements in the bridge construction is reducing the onsite construction time and erecting the bridge elements in the offsite area. This approach can reduce the project cost due to offsite manufacturing, improve safety, and quality that leads to improving the long-term performance of the bridge. The proper design and planning should be considered in the ABC to make the ABC advantages significantly pronounced in comparison to the conventional bridge construction. While this study focuses on ABC substructure, it is also realized that design and type of substructure is highly dependent on the design and type of superstructure as well as construction methods employed for the ABC project. Therefore, this section begins with a review of existing selection processes and factors involved for construction methods and superstructure, followed by interrelation between these and selection of substructure. Furthermore, additional factors that can independently affect the selection of substructure will be investigated.

The Federal Highway Administration (FHW) provides a flowchart that, in general and mostly quantitative terms, can help to identify whether implementing ABC method in a project is beneficial (Figure 3-1) [52]. The decision makers including the owners and contractors who are responsible for selecting the construction method should consider the flowchart and factors in utilizing the prefabricated elements in the construction of a bridge. These factors include applicability of design, the ability of contractor and supplier, accessibility to the job site, cost, and, schedule of project, and track of the project. The other factors include responsibility and commitment of contractor and owner and risk of the project. It should be noted that the owner prefers to complete the job with a minimum price and time with high durability and integrity. However, the contractor prefers to earn a reasonable profit from the project.

Moreover, some state DOT’s and agencies provide their own decision-making flowchart to investigate the efficiency of implementing ABC or conventional bridge construction. These agencies make some modification to FHWA flowchart to meet their own goals and concerns. For instance, the Wisconsin Department of Transportation (WisDOT) investigates the use of ABC method in comparison with a conventional method by providing a decision-making matrix and flowchart (Figure 3-2, 3-3) [53]. The applicability of ABC method for a particular project is identified by defining a score for the project according to the different factors including the condition of project, cost, risk, and environment. In this way, quantitative measures are inserted into the decision-making process. When the project has a high score, the ABC is justified to be used. When the score is low, the conventional construction method should be considered. When the rating is in marginal between using ABC method and conventional construction method, the overall cost and engineering judgment should be considered to determine if ABC method should be considered. The score calculated using decision-making matrix is then used in the flowchart (Figure 3-3) to decide whether the ABC method is applicable to the project. In this process, the project information and engineering judgment are the primary tools for decision making.

In summary, in the case of new bridge construction, the designer has the freedom to select the most appropriate system for implementation. Accordingly, the designer is not constrained by an existing substructure.

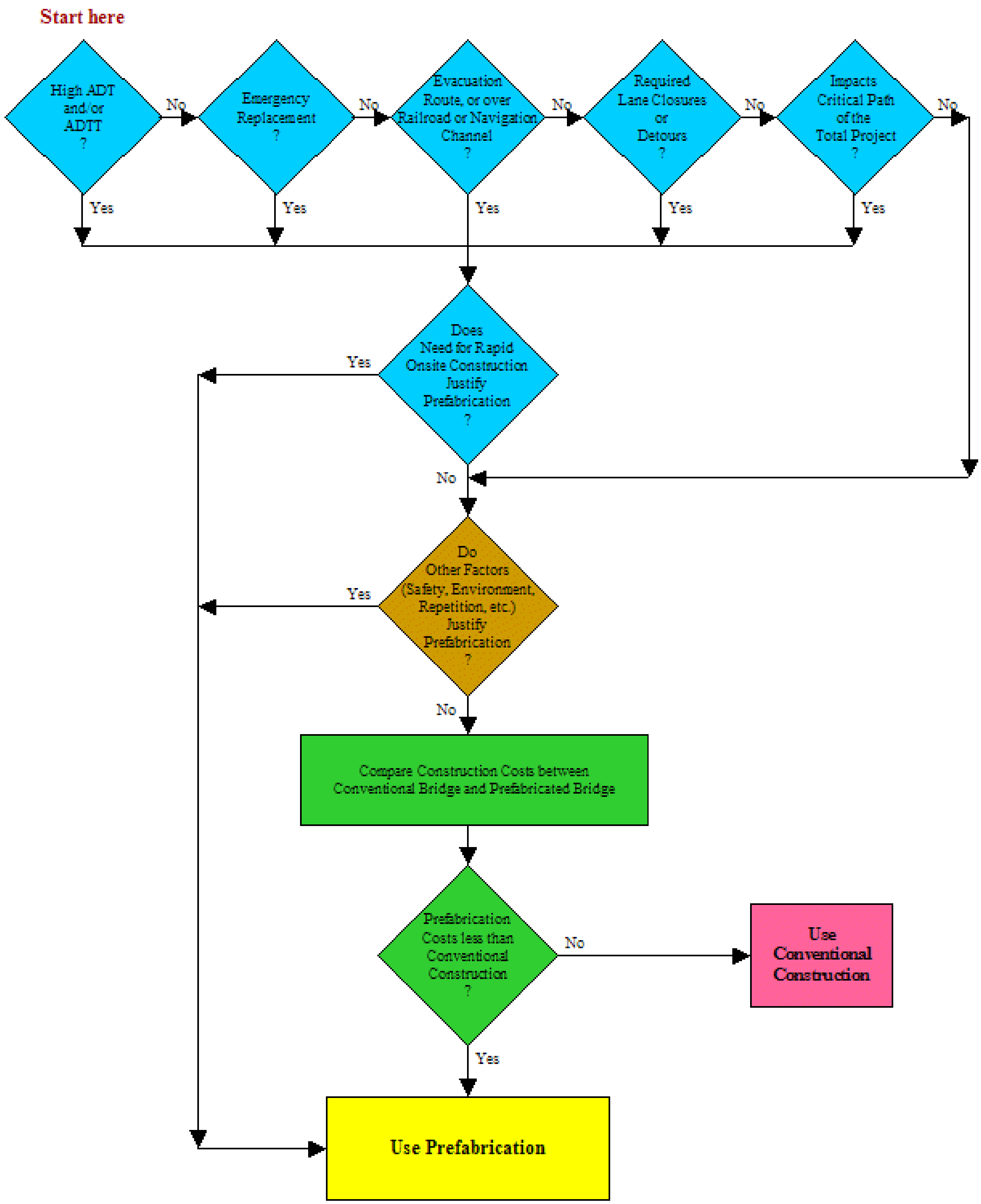


Figure 3-1: Decision-making flowchart to use prefabricated elements in bridge construction [52]

% Weight	Category	Decision-Making Item	Possible Points	Points Allocated	Scoring Guidance
17%	Disruptions (on/under Bridge)	**Railroad on Bridge?**	8		0 No railroad track on bridge 4 Minor railroad track on bridge 8 Major railroad track on bridge
		Railroad under Bridge?	3		0 No railroad track under bridge 1 Minor railroad track under bridge 3 Major railroad track(s) under Bridge
		Over Navigation Channel that needs to remain open?	6		0 No navigation channel that needs to remain open 3 Minor navigation channel that needs to remain open 6 Major navigation channel that needs to remain open
8%	Urgency	**Emergency Replacement?**	8		0 Not emergency replacement 4 Emergency replacement on minor roadway 8 Emergency replacement on major roadway
23%	User Costs and Delays	**ADT and/or ADTT** (Combined Construction Year ADT on and under bridge)	6		0 No traffic impacts 1 ADT under 10,000 2 ADT 10,000 to 25,000 3 ADT 25,000 to 50,000 4 ADT 50,000 to 75,000 5 ADT 75,000 to 100,000 6 ADT 100,000+
		Required Lane Closures/Detours? (Length of Delay to Traveling Public)	6		0 Delay 0-5 minutes 1 Delay 5-15 minutes 2 Delay 15-25 minutes 3 Delay 25-35 minutes 4 Delay 35-45 minutes 5 Delay 45-55 minutes 6 Delay 55+ minutes
		Are only Short Term Closures Allowable?	5		0 Alternatives available for staged construction 3 Alternatives available for staged construction, but undesirable 5 No alternatives available for staged construction
		Impact to Economy (Local business access, impact to manufacturing etc.)	6		0 Minor or no impact to economy 3 Moderate impact to economy 6 Major impact to economy
14%	Construction Time	**Impacts Critical Path of the Total Project?**	6		0 Minor or no impact to critical path of the total project 3 Moderate impact to critical path of the total project 6 Major impact to critical path of the total project
		Restricted Construction Time (Environmental schedules, Economic Impact – e.g. local business access, Holiday schedules, special events, etc.)	8		0 No construction time restrictions 3 Minor construction time restrictions 6 Moderate construction time restrictions 8 Major construction time restrictions
5%	Environment	**Does ABC mitigate a critical environmental impact or sensitive environmental issue?**	5		0 ABC does not mitigate an environmental issue 2 ABC mitigates a minor environmental issue 3 ABC mitigates several minor environmental issues 4 ABC mitigates a major environmental issue 5 ABC mitigates several major environmental issues
3%	Cost	**Compare *Comprehensive* Construction Costs** (Compare conventional vs. prefabrication)	3		0 ABC costs are 25%+ higher than conventional costs 1 ABC costs are 1% to 25% higher than conventional costs 2 ABC costs are equal to conventional costs 3 ABC costs are lower than conventional costs
18%	Risk Management	**Does ABC allow management of a particular risk?**	6		0 - 6 Use judgment to determine if risks can be managed through ABC that aren't covered in other topics
		Safety (Worker Concerns)	6		0 Short duration impact with TMP Type 1 3 Normal duration impact with TMP Type 2 6 Extended duration impact with TMP Type 3-4
		Safety (Traveling Public Concerns)	6		0 Short duration impact with TMP Type 1 3 Normal duration impact with TMP Type 2 6 Extended duration impact with TMP Type 3-4
12%	Other	**Economy of Scale** (repetition of components in a bridge or bridges in a project) (Total spans = sum of all spans on all bridges on the project)	5		0 1 total span 1 2 total spans 2 3 total spans 3 4 total spans 4 5 total spans 5 6+ total spans
		Weather Limitations for conventional construction?	2		0 No weather limitations for conventional construction 1 Moderate limitations for conventional construction 2 Severe limitations for conventional construction
		Use of Typical Standard Details (Complexity)	5		0 No typical standard details will be used 3 Some typical standard details will be used 5 All typical standard details will be used
			Sum of Points:	0	(100 Possible Points)

Figure 3-2: WisDOT ABC decision-making matrix [53]

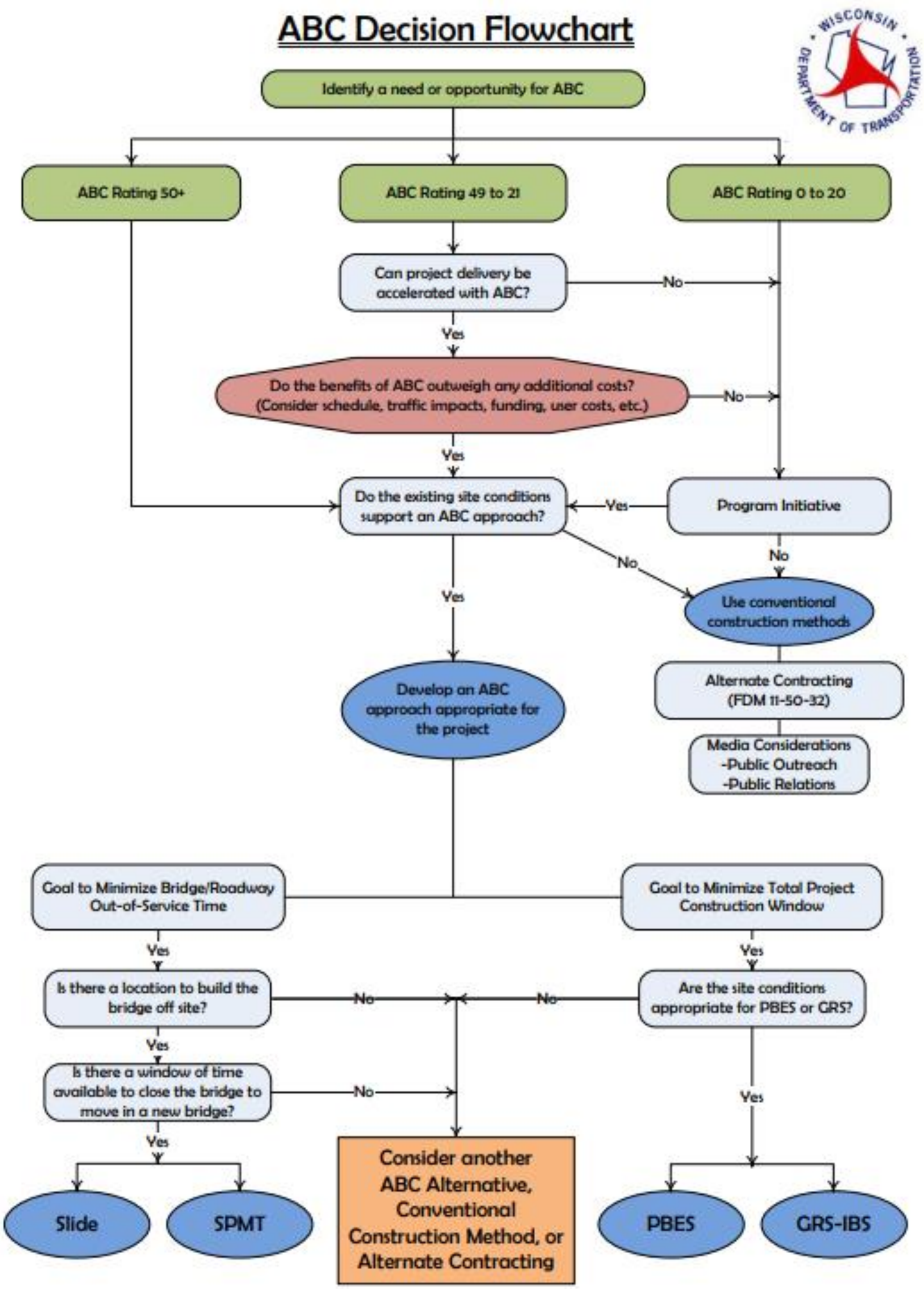


Figure 3-3: WisDOT decision-making Flowchart [53]

3.1 Major Parameters Affecting selection of bridge type in general

The case of new bridge construction affords the designer the freedom to select the most appropriate system for implementation. There are some major parameters that affect not only the decision making for the construction method, but also provide constraints or facilitate selection of details at system and element level. Common factors to be considered in the selection of new ABC Bridge components are shown in Figure 3-4 and include;

Time Constraint

The main reason of using ABC technique in construction of bridges is reducing the time of construction. However, not all projects have the same level of time constraint, and not all ABC methods can accommodate every time constraint. ABC construction method, and type of prefabricated elements and subsystems can be selected to accommodate the time constraint. Constrains can be caused due to effect on traffic mobility, weather conditions, bridge site conditions, and environmental conditions.

Risk and Cost of the project

Transporting the precast bridge components may drive the cost of bridge construction up. Also, transporting the elements and bridge modules into the site may cause damage to the components, pose safety concerns, and may need special shipping method that can increase the risk to the project. There are also risks involved in lifting, moving, and installation of prefabricated elements and systems. Such risks should be evaluated and compared among various ABC methods, and between ABC methods and conventional and cast-in-place construction. The consequences of these risks can increase the cost of the project. As an example, if higher risks exist for long distance hauling and transportation, fabricating the precast components near the bridge location may be preferable. In the same manner, if risks are high for transportation and the site conditions would not allow near-site fabrication, a conventional cast-in-place method may be more advantageous. Another major parameter that can affect the risk and cost involved in ABC projects relates to availability of contractors and their capabilities. It is sometimes the case that local contractors, who have cost advantages for being local, may not have qualification, equipment and skills necessary for implementation of a certain ABC method. Also, availability and proximity to the bridge site for precast plants capable of prefabricating the bridge elements may have significant effect on both costs and risks.

Environmental considerations

In addition to the other considerations, construction impacts into the environment that needs to be considered. Water activities, as an example, may have a significant impact on the overall project delay. Due to that, construction may be restricted to a portion time of year. Therefore, the construction time plays a significant role in the selection of construction method and bridge type especially in the construction of substructure that leads to the necessity of using ABC method.

Geometric Considerations

Geometric considerations include the bridge span, width, right of way alignment, elevation, and connections to existing roads on both sides of the bridge. As mentioned, bridge span or girder spacing is normally selected based on the shipping considerations. Once the prefabricated modular systems and bridge elements are fabricated near the site, it is possible to increase the girder spacing over 130 ft. For bridge span up to 130 ft. the pre-tensioning method without the post-tensioning method is used in the site. Once the bridge span is over 130 ft., the post-tensioning technique needs to be used to extend the bridge span length [47]. In the case of substructure elements, when the weight of elements and their shipping is in concern, using element segments and connecting them on the site is the option.

Site Condition and Accessibility

In addition to the geometric and structural requirements that come to play in conventional bridge design, additional consideration must be given to the space needed to manufacture large parts of the bridge on-site or nearby the bridge final position and the space necessary to maneuver such large elements to their final position. Site considerations also include the specifics of the bridge site, such as local space available for erection and assembly of bridge components, existence of deep water or rapid currents, adjacent property use and setbacks, width and vertical clearance of roads leading to the project site. If water navigation is used to transport bridge elements, the width and depth of water in the area are important site conditions. It also includes human activities, driving habits, and availability of alternative transportation facility in the area. Such factors impact the space available for the project and may favor specific construction types. For instance, the existence of steep slopes may limit the feasibility of transportation of large bridge segments or may require special equipment to allow bridge transportation and erection. When there is a limitation in site accessibility, using the systems with smaller sizes elements are preferable.

Design Constraints and Considerations

In the case of new bridge construction, the design considerations include the number of spans, span length, type of support, type of bridge structure, connection type, seismicity of the bridge location, foundation, and layout of bridge roadway connection with other roads. In some instances for example, implementing a joint less bridge design, full moment connection between bridge members, integral abutments or similar considerations can provide higher integrity and durability for the bridge when compared to other designs.

Compatibility between Superstructure and Substructure, and between Substructure and Foundation

In addition to geometric compatibility, the bridge elements and units are expected to be compatible in design and construction with each other. For instance, the performance anticipated for connection between super- and substructure may favor or limit the use of one or another type of substructure.

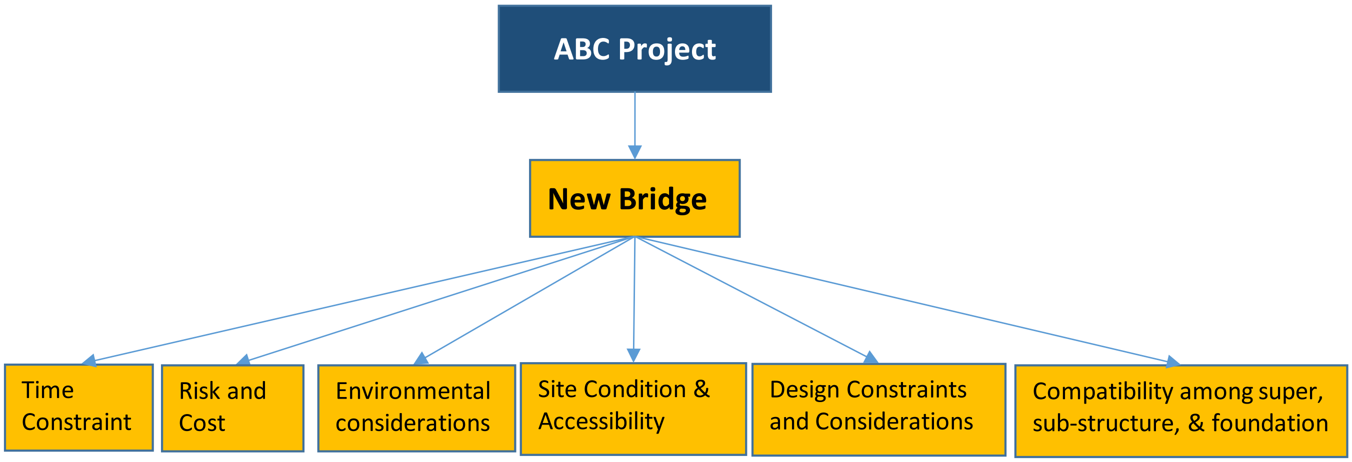


Figure 3-4: Parameters affecting selection of ABC components

Substructure connects superstructure to the foundation and facilitates the transfer of load to the ground. Therefore, it is obvious that selection of substructure in general will depend on what superstructure has been chosen for the bridge, what option for the foundation has been considered, and what other effective conditions such as access, site, and design requirements would influence this selection. ABC bridge superstructure can be selected according to the process reviewed in the following sections. The substructure in fact seems to have to be strongly dependent on the superstructure that is in direct contact with imposed loading, and also on the foundation that transfers the load to the ground. It is the understanding of the authors that substructure has to be selected such that it accommodates and adapts to the needs and conditions of superstructure and foundation as a link system. In the next sections, it is attempted to describe the selection criteria for type and method of construction for superstructure and foundation, and to see how these will affect the selection of the substructure systems and components.

3.2 Selection of Construction Method and Type of Superstructure

In a study conducted by FHWA, the applicability of using different ABC methods by considering the site accessibility constraints is investigated [1]. The ABC methods are identified in chapter 2 and summarized in Table 3-1. To determine the proper construction method, the ABC projects are categorized in construction of a bridge over roadways or land (Figure 3-5), over railroad or transit (Figure 3-6), and over water or wetland (Figure 3-7).

As shown in Figure 3-5, significant factor in selecting the best ABC method is the accessibility to the project site. In the construction of bridge and superstructure over roadways or land, the availability of a clear travel path is necessary to use the SPMT method. In this method, to reduce the axle's loads to the allowable load, the SPMT should be adjusted by adding axles. In this case, lane closure, clearance height, and an available detour also should be considered. However, when a space directly adjacent to the bridge is available for the erection of bridge superstructure, the lateral skidding is a viable construction method. When the adjacent space and clear travel path is not available, the construction-in-site using prefabricated elements and lifting devices is viable. It should be noted that construction using prefabricated elements is a feasible method for all three site conditions [1]. When the bridge is crossing a body of water, it can provide an obstacle or opportunity to use ABC methods [52]. In this situation, the prefabricated elements may be delivered to the site using barges if navigation constriants allow.

In constructions over the railroad or transit, the railroad same as water crossing can provide obstacle or opportunity in the bridge construction [1]. It might be possible that heavier bridge components are transferred using the railroad. However, the clearance height and closure period should be considered. Another potential factor is geotechnical constraints relating to the stability, settlement, and capacity of the soil. When a crane is used at the site that normally is accompanied with heavy concentrated load, its effect on the settlement and capacity of soil needs to be considered as well.

Table 3-1: ABC methods

ABC method	Comment
Self-Propelled Modular Transporters (SPMT)	SPMTs is a vehicle that is used to carry, lift, and place heavy loads like bridge elements. The installation time of bridge using this transporter depends on the carrying distance.
Longitudinal launching	The bridge can be constructed in the launching pit or transferred to launching pit using SPMT. The bridge is jacked out horizontally over the abutment to be installed in position.
Horizontal skidding or sliding	Superstructure is constructed parallel to the bridge placement location on the temporary supports. The hydraulic system or cables are using to move the superstructure transversely and place the superstructure. This method also can be used to slide the superstructure to the existing bridge after demolishing the existing superstructure
Conventional cranes	Can be used to install and place the prefabricated bridge elements
Other heavy lifting equipment and method	Strand jack lifting pulls up the bridge. Climbing jack lifting push up the bridge. Another technique is transverse pivoting which can rotate the bridge to its location precisely.

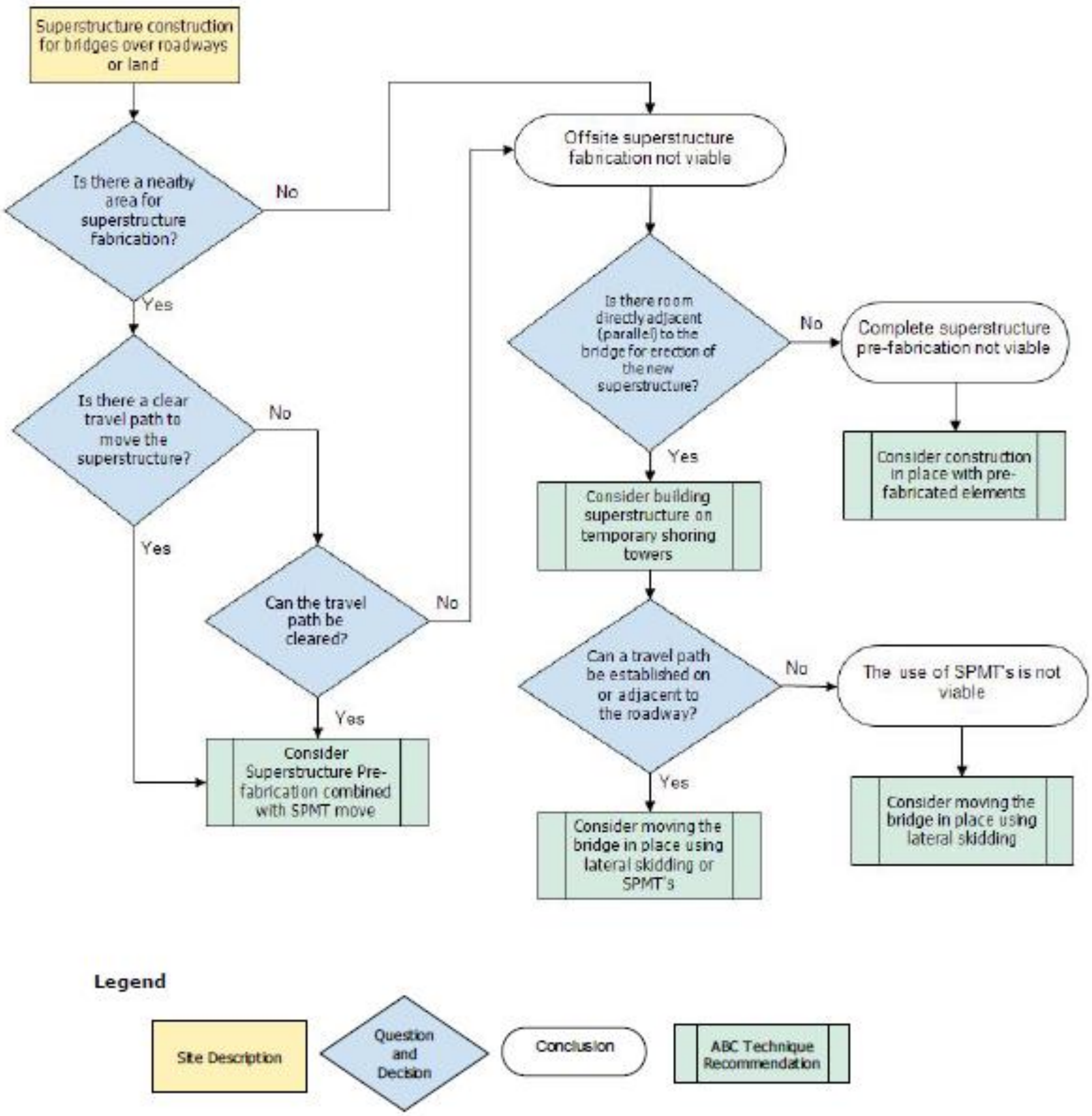


Figure 3-5: Decision flowchart for superstructure construction over the roadways [1]

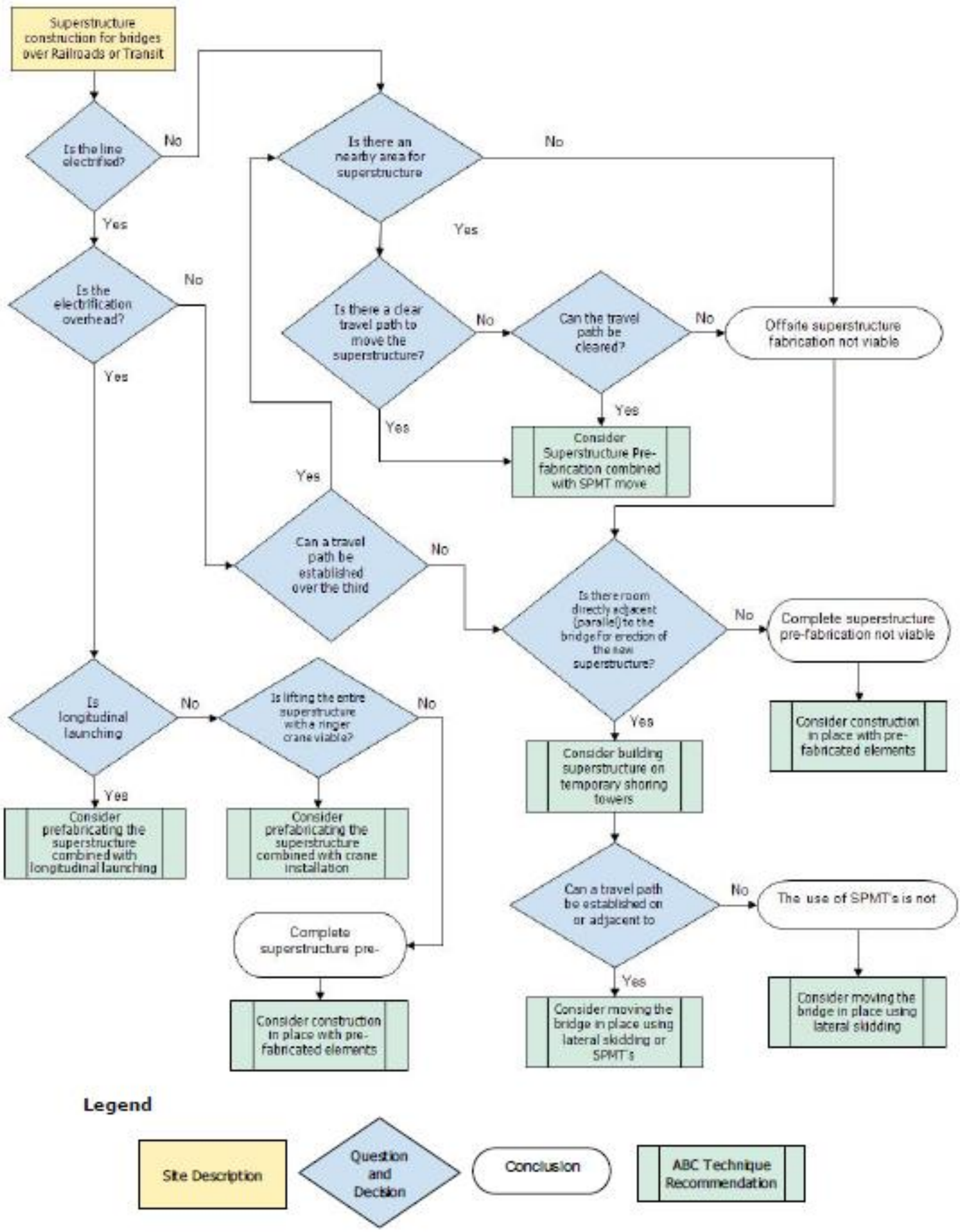


Figure 3-6: Decision flowchart for superstructure construction over the railroads [1]

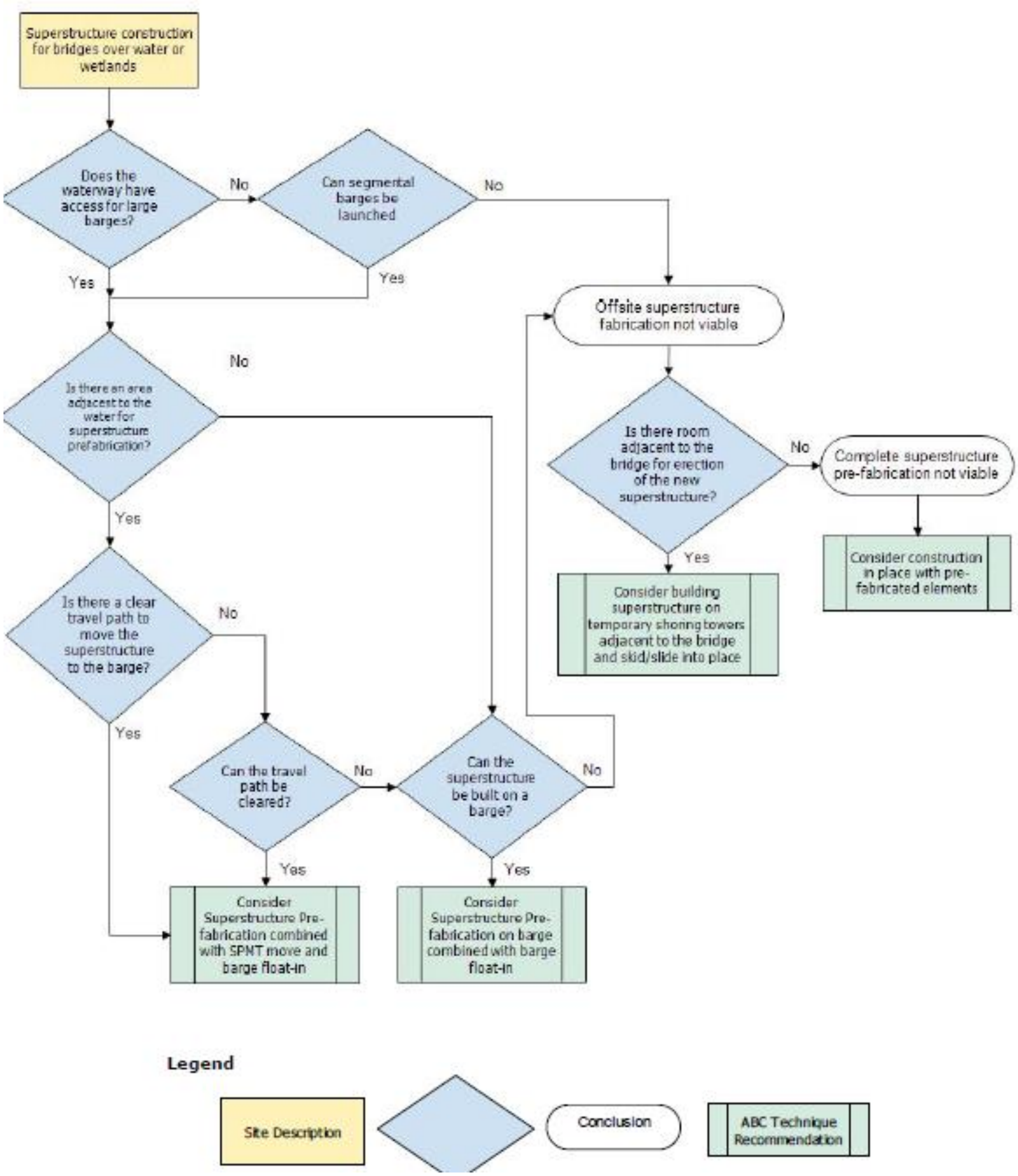


Figure 3-7: Decision flowchart for superstructure construction over the water [1]

3.3 Available Selection and Design Considerations for Substructure

The FHWA report provides the decision flowchart for construction of ABC projects substructure (Figure 3-8) [1]. The usage of this chart is mostly for replacement of existing bridges and less usable for the new bridge construction. Some stakeholders have questioned the need for using ABC for constructing substructure for new bridges arguing that the time is not a constraint in this case. However, there are many factors involved in construction that may turn the tide to the benefit of ABC for substructure. Construction of bridge substructure in conventional manner takes most of the bridge construction time. To reduce construction time, the use of prefabricated elements and modular systems are beneficial and very effective. The prefabricated elements and modular systems are normally built in the shop or near the site and assembled at the site. In addition to time saving, this provides for better quality, safety, and control on project schedule and cost. The substructure can be placed over deep or shallow foundation according to the soil and site conditions [47]. This study attempts to provide guidelines for selection of substructure for ABC projects not only for the case of replacement of existing bridges, but also for construction of new bridges. Similar considerations may result in viable options for the use of ABC foundations.

The use of modular abutment that can accommodate a joint-free and maintenance-free substructure element is preferable when targeting to reduce the construction time. The modular abutment can be designed and constructed integrally or semi-integrally with the superstructure. In that point, the use of integral abutment is preferable for providing joint-free riding surface at abutment and full moment connection between substructure elements that can emulate the cast-in-place construction [47]. Another factor should be considered in the construction of substructure over the water is the water activity. Water activity timing and navigation restrictions may affect the design, construction method, and selection of type of the substructure.

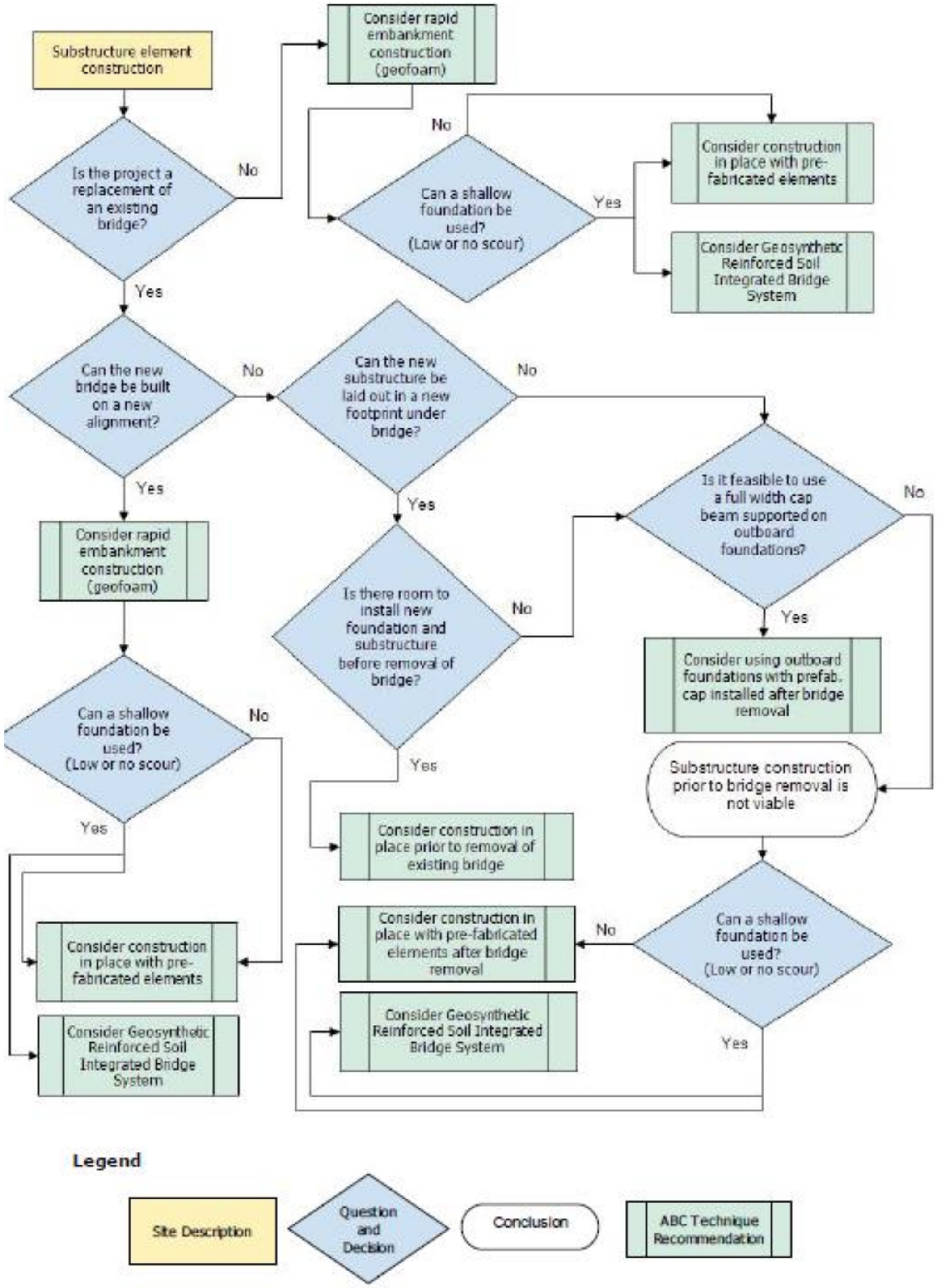


Figure 3-8: Decision flowchart for substructure construction [1]

3.3.1 Selection of Substructure Elements and Systems

The type of substructure elements and systems depends on; a) parameters affecting selection of ABC methods and elements in general as described in Figure 3-4, b) compatibility of substructure with superstructure and foundation, and c) parameters specific to the substructure (Figure 3-9).

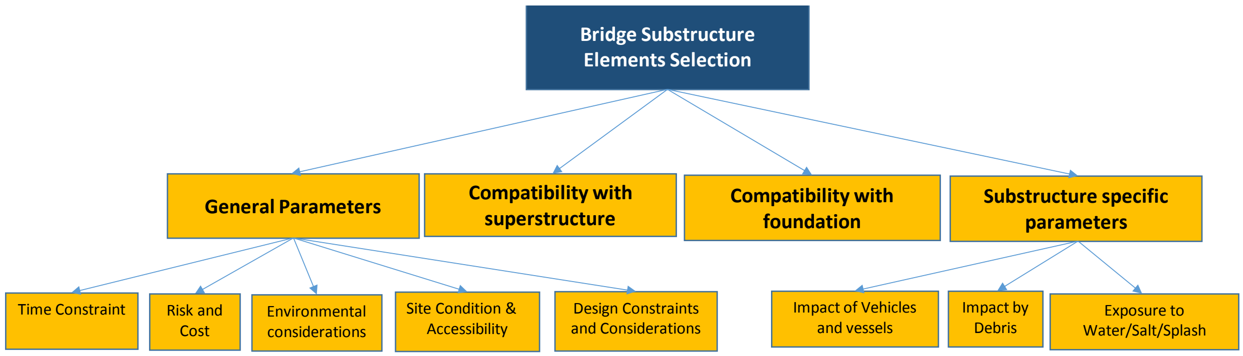


Figure 3-9: Bridge substructure element selection parameters

3.3.2 Parameters affecting the selection of bridge elements and construction methods in general

As discussed in the previous section related to selection of construction methods and superstructure element and system type, a set of general parameters discussed on Figure 2 influence the selection process with accessibility and availability of space having the major impact. Apparently, these parameters will affect in the same way the selection of substructure as well. For example, if there is no accessibility to transport large systems to the site, individual elements installed by conventional crane have to be used also for the substructure, the same way as for the superstructure. Therefore, for the substructure, the type of elements and methods selected for superstructure should be followed in general. Accordingly, there is no need to repeat the selection process for substructure as far as general parameters are concerned. In the same manner, this also applies to the construction method to be used for substructure, and the size of elements or subsystems. Beyond these preliminary decisions that will follow those of the superstructure, following describes the specifics on substructure in accordance with compatibility with superstructure and foundation, as well as parameters specific to substructure.

Compatibility of Substructure with Superstructure and Bridge Configuration

In addition to geometric compatibility, the bridge elements and units are expected to be compatible in design and construction with each other. For instance, the performance anticipated for connection between super- and substructure may favor or limit the use of one or another type of substructure. For fully-integral, semi-integral, or siding connection with the superstructure, the abutment or pier cap shall accommodate the transfer of moment and shear as per design and therefore these conditions will become defining parameters for the type of the pier or abutment.

Compatibility of Substructure with Foundation

Substructure is a component of the bridge that connects superstructure and substructure together and transfer loads from superstructure to foundation. Therefore, the compatibility of substructure with superstructure as well as foundation in design and construction is necessary for integrity and unity of bridge. For instance, the seismic condition of soil may constrain the use of some types of connections between foundation and substructure, causing limitation in selection of substructure element, design, and construction type.

3.3.3 Parameters Specific to Substructure

There are some factors that may only affect the selection of substructure. One of them is exposure of substructure to water, salt, or splash. In this case, special considerations should be considered to select the materials and elements of the bridge substructure that provide for more durability in the related harsh and corrosive environment. Additionally, in some cases the bridge substructure may be impacted by vehicles for the case of bridge over roadway, or in the case of bridge across waterways by debris and vessels. This may result in the use of protective elements around the piers or the use of pier wall in the substructure.

3.3.4 Selection of Substructure based on Compatibility with Superstructure and Substructure-specific Parameters

In this section, a flowchart for selection of substructure for ABC projects is developed based on the superstructure system and ABC method considering interrelations and other parameters involved. Similar to the selection of ABC method flowcharts, the substructure selection can be divided into three flowcharts based on the construction of a bridge over roads (Figure 3-4), over railroads (Figure 3-5), and over wetlands (Figure 3-6). By use of these flowcharts, it is possible to define the ABC method and subsequently identify the superstructure systems. It should be noted that the use of prefabricated elements is viable for all types of ABC methods. Nevertheless, prioritization for the use of ABC method should be applied based on all factors involved in selection process including but not limited to cost, safety, quality, and onsite construction time. Consequently, the substructure system can be selected according to the ABC method and the parameters listed in the previous section. A flowchart that can be used to select the substructure types and components is shown in Figure 3-10a. As shown in this flowchart, the substructure includes pier and abutment system, buried bridges and modular culverts. The flowchart is divided to its main segments, and for clarity the segments are presented in Figures 3-10b through 3-1-e. The flowchart in Fig. 3-10b will lead to the type of substructure system based on span length and other constraints. As the type of substructure is selected, the substructure elements and systems can be selected using Figs. 3-10c to 3-10e for pier and abutment system, buried bridges, and culverts, respectively.

When using pier and abutment system, to select the pier elements, it should be considered if piers are affected by the errant vehicle or there is a possibility to collect derbies between piers when the bridge passes over the wetland. In these cases, the wall piers should be used instead of piers. In other cases, the piers and pier columns can be used. In this case, the integration of pier cap or pier wall cap with the superstructure should be considered to determine the connection and accommodation require to join the pier cap and superstructure. Also, this should be considered that cap may be placed directly over the pile or it may be placed over the pier column. Consequently, the pier column should be supported by footing. As shown in Figure 3-10c, abutment system includes wing wall and abutment wall. Wing wall can be constructed using precast elements or as a modular unit. In abutment wall, the integrity of abutment with the superstructure is important. When the integration of abutment with superstructure is vital, the use of fully or semi-integral abutment is needed. When the integrity of abutment with superstructure is not important, the cantilever, spill-through, or stub abutment can be used. It should be noted that the use of fully integral abutment that is constructed with the superstructure is preferable due to its full moment connection with the superstructure as well as increasing the speed of construction.

The type of buried bridges can be narrowed down based on availability, environmental effects and span as shown in Fig. 3-10d. Similar process can be applied for selection of culvert elements from Fig. 3-10-e.

3.3.5 Suitability of Substructure Types with Respect to Foundation

In this section, considering interrelations and other parameters involved, a flowchart for selection of substructure for ABC projects is developed based on the foundation system and the ABC method. As shown in Figure 3-10, the selection of substructure for new bridges can be based on whether the bridge foundation is deep or shallow. The selection of deep or shallow foundation can be based on the site conditions, existence of river, soil conditions, etc., which are discussed in the next sections. However, in this section, a flowchart that can be used to select the substructure types and components based on the foundation is presented (Figure 3-11).

When a deep foundation such as pile foundation is used for the bridge, it may also serve as a bridge pier and connect directly to pier cap (also serve as pile cap). In this case, the bridge does not need a separate pier. When the deep foundation cannot be used as a pier, a pile cap is needed. Pile cap function as it relates to connection to substructure would be like a shallow foundation. Therefore, a pier column or pier wall is required in order to transfer superstructure loads to the foundation. The type of substructure elements will have to satisfy the flowchart presented earlier in Figure 3-10. After selecting the pier wall or pier column, the type of pier cap can be determined by considering the compatibility with the superstructure and connectivity design between substructure and superstructure.

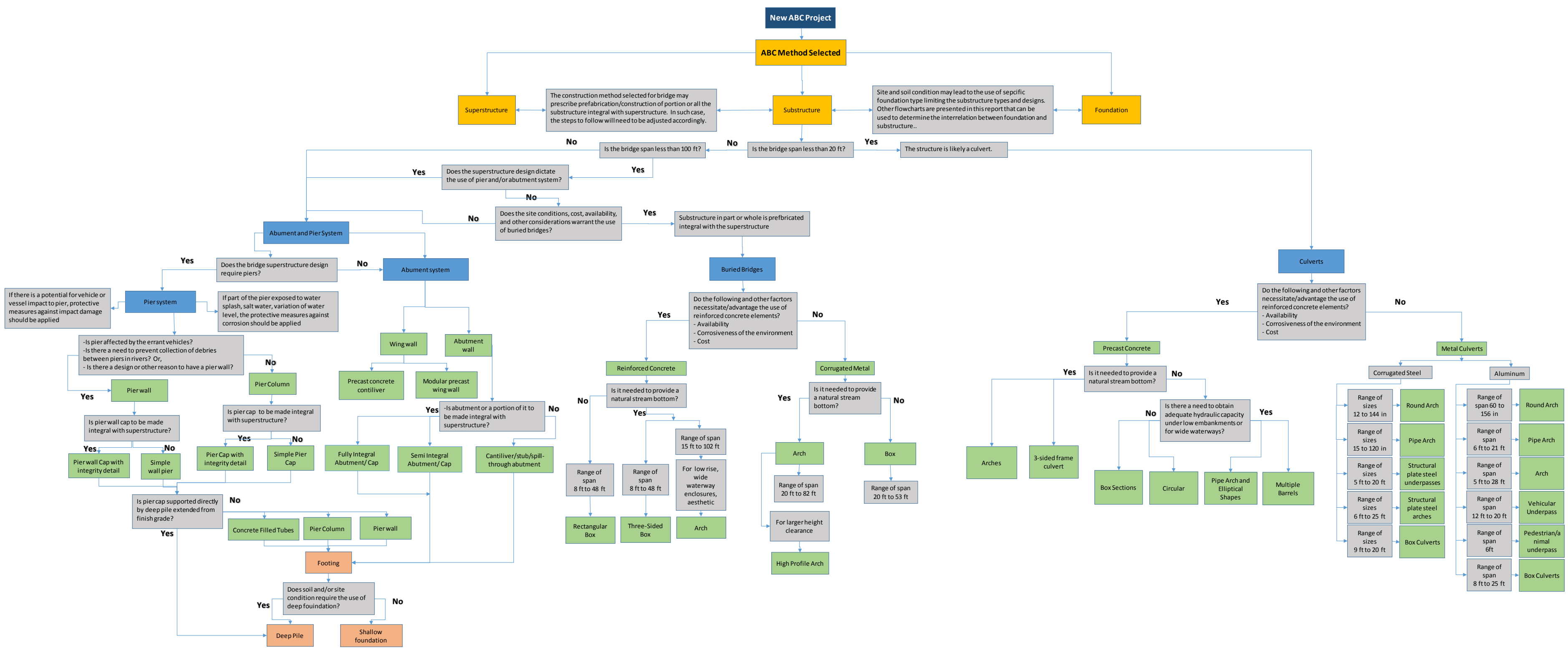


Figure 3-10a: Flowchart for selection of substructures

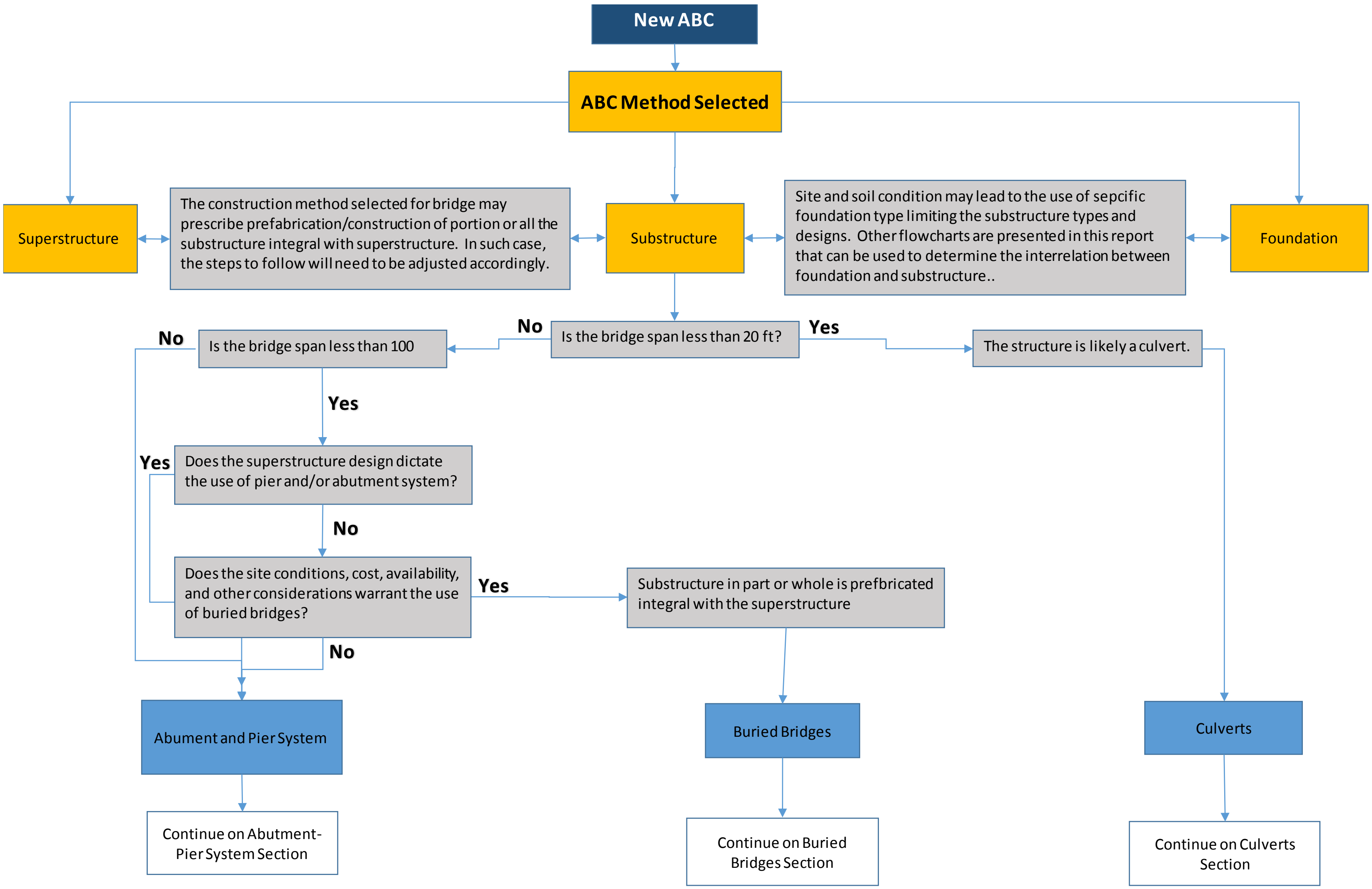


Figure 3-11b: Flowchart for selection of substructure system

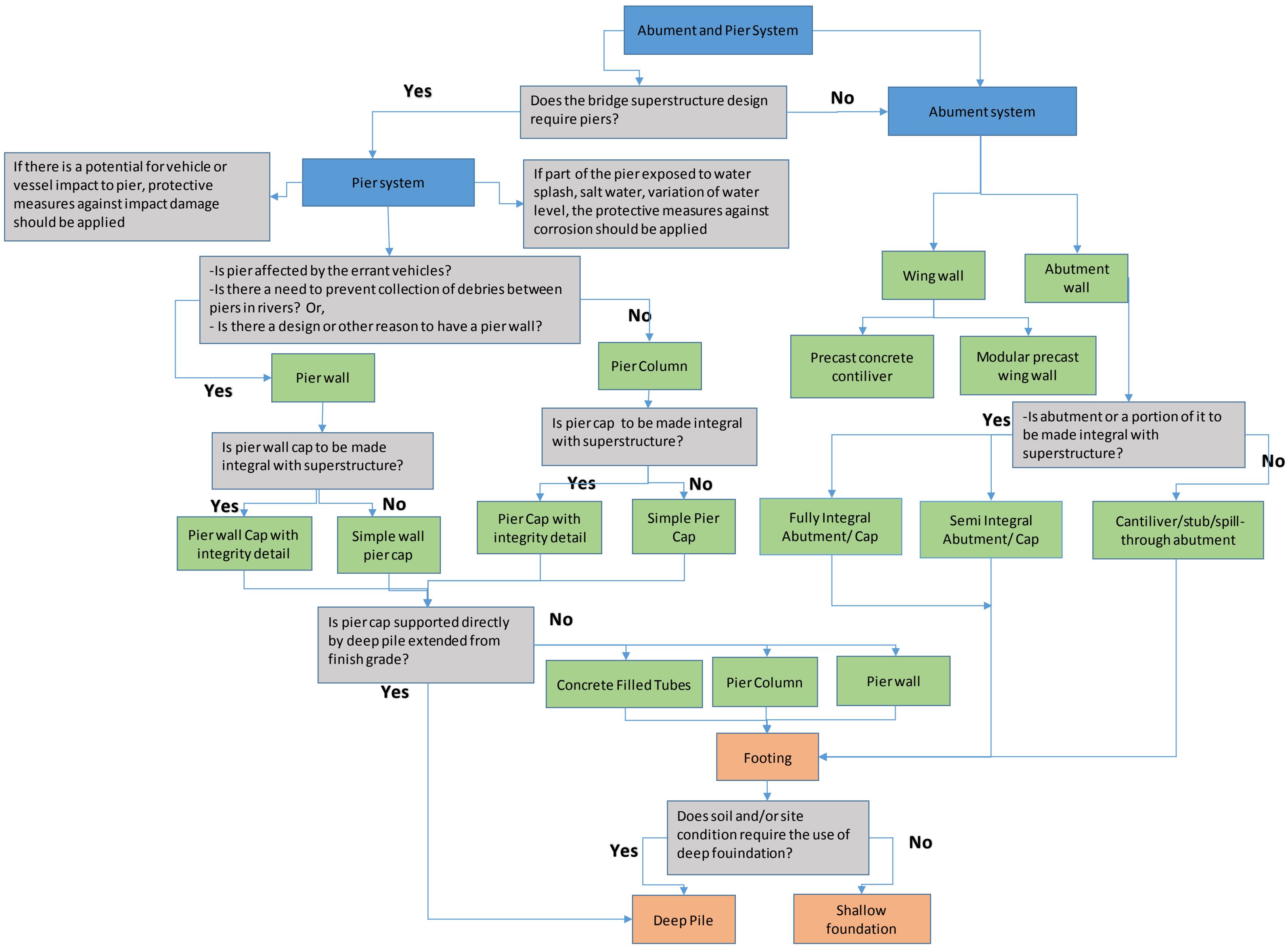


Figure 3-12c: Flowchart for selection of substructure elements for pier and abutment system

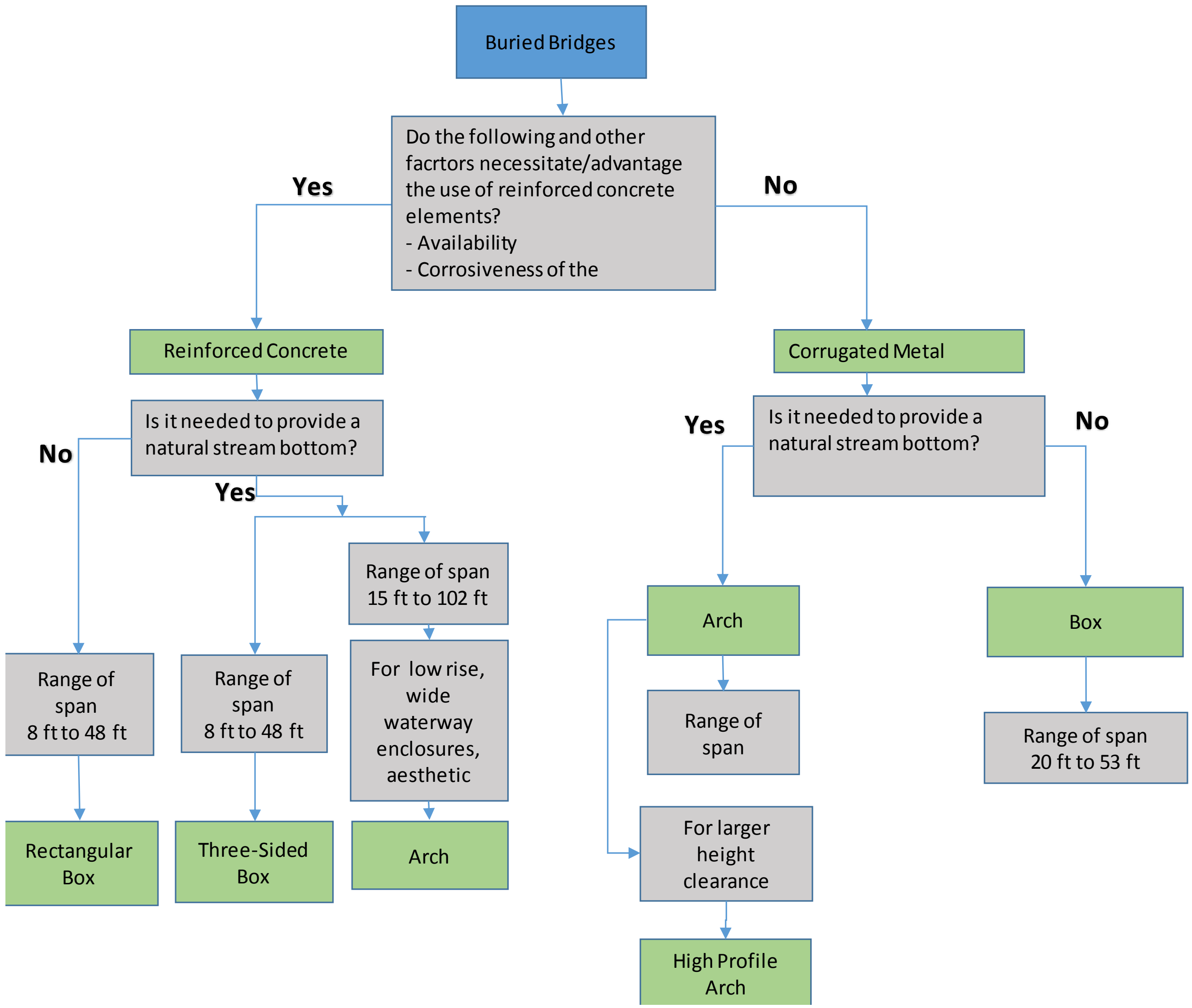


Figure 3-13c: Flowchart for selection of substructure elements for buried bridges

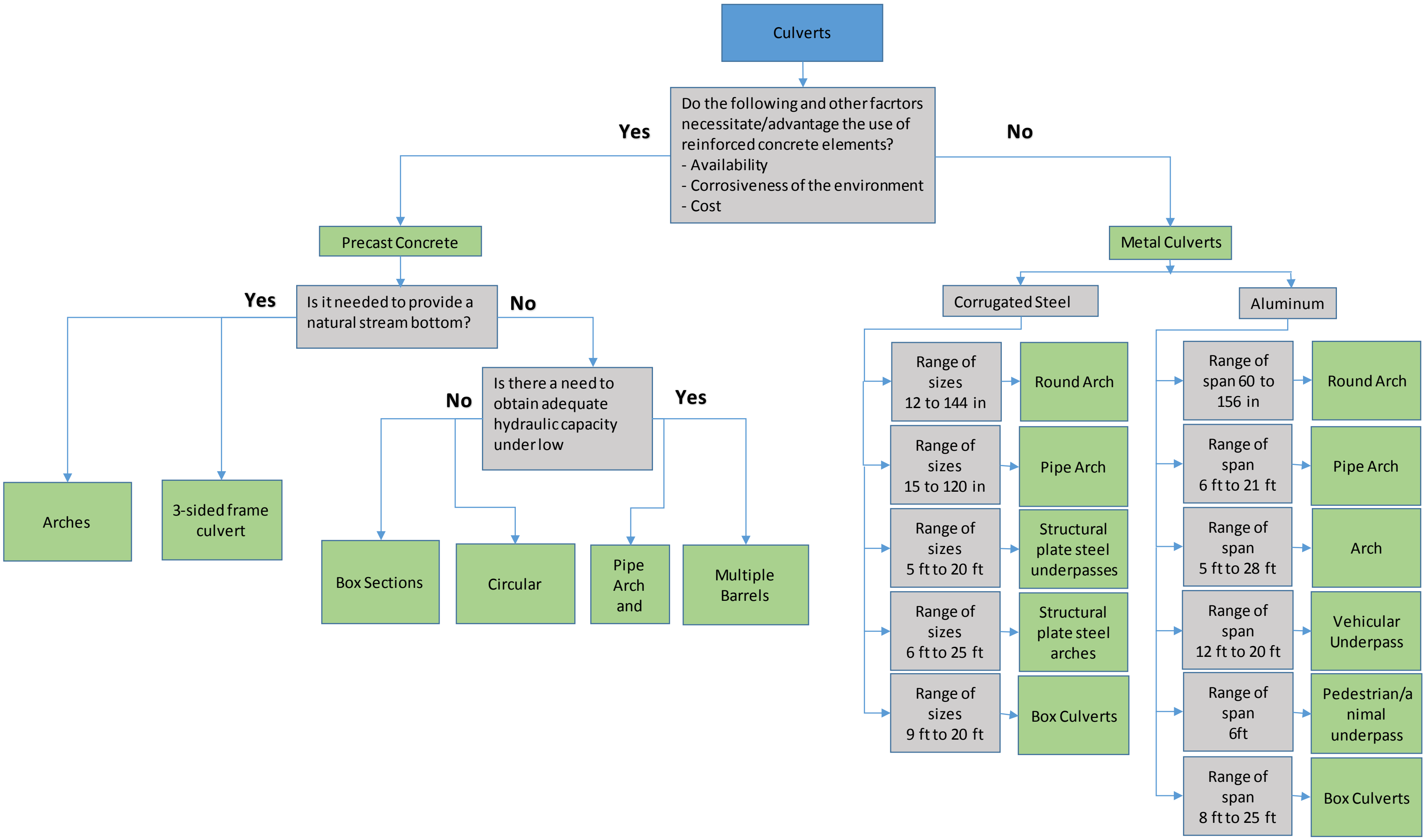


Figure 3-14d: Flowchart for selection of substructure elements for culverts

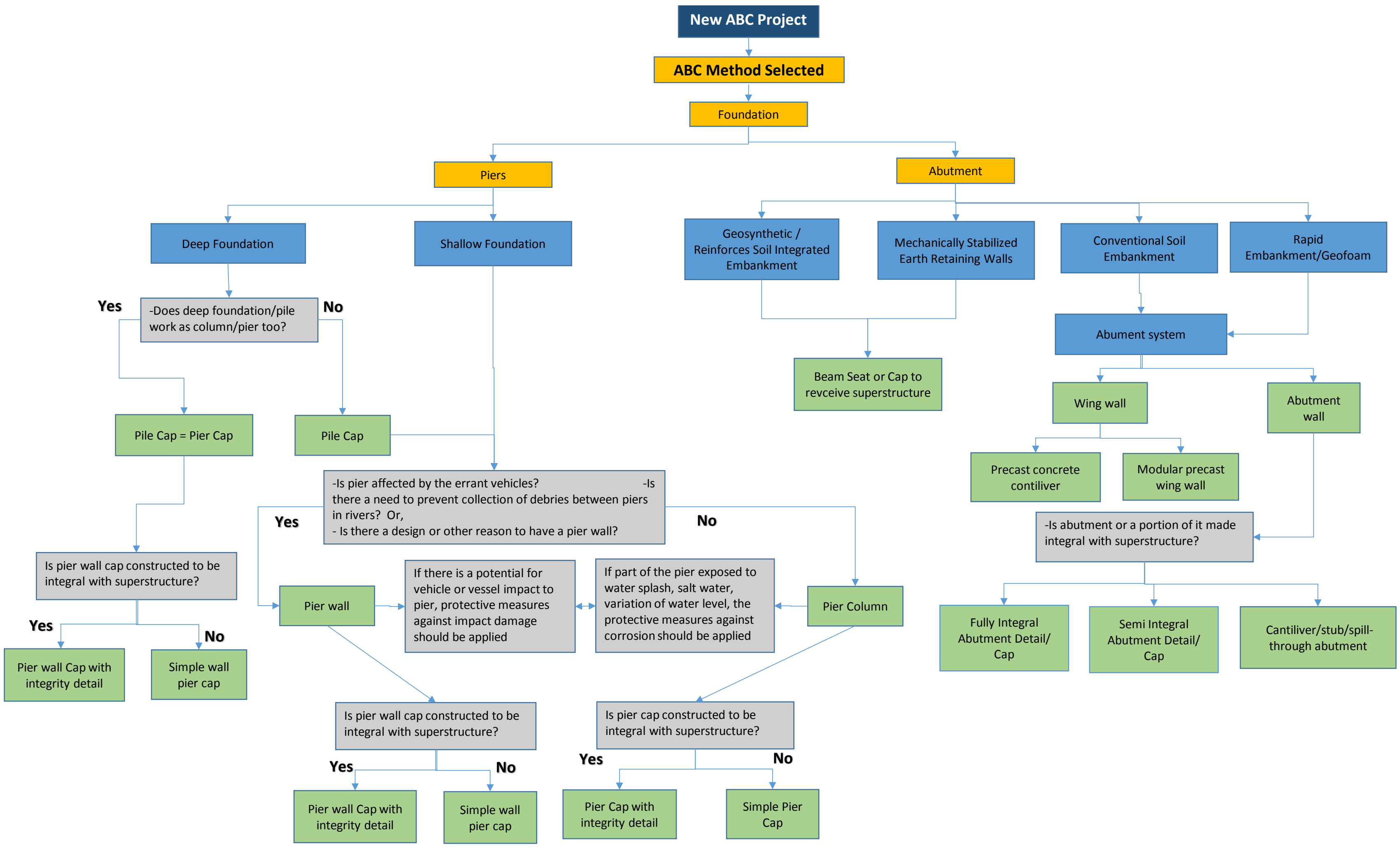


Figure 3-15: Flowchart for selection of substructures with respect to foundation type

3.4 Selection and Design Considerations for Foundation

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3.5 Design considerations for Connections

Design and type of joints and connections between the bridge elements and modular systems influence the ABC speed and integrity. The type of connection can affect live load distribution, seismic performance, rideability, and durability of the bridge. In addition, connection type plays a prominent role to achieve a desirable structural performance and bridge construction time. The designer needs to develop the bridge structure type and ABC method according to the site and time restrictions. In this case, the connections between modular elements, superstructure and substructure, and superstructure elements play an essential role to drive a desirable performance and construction timing. Connections can define how easily the modular units and bridge elements connect and assemble together as well as emulating the cast-in-place construction. Therefore, the construction time of connections depends on curing time of the closure pour, type of connection, and number of connections [47].

In superstructure, to improve joint performance, post-tensioning technique can help to close shrinkage cracks in the joints, prevent cracking and improve load transfer between connected elements. Post-tensioning technique can be used in female-female shear key joints or match cast with epoxy joints. Post-tensioning technique can also be used with closure pour [47]. The following are the considerations for superstructure connections:

-Providing full moment connection, shear transfer, or free rotation or sliding resulted from design and practical consideration

-Providing a durable connection equal to or surpassing precast deck

-Suitability of connection for heavy truck traffic

-Provide quality for riding surface

-Eliminating the need for overlays despite overlays increasing the construction tolerance

-Eliminating the need for post-tensioning in the field if possible

-Providing for fast setting and rapid strength gain

By considering the above factors for the superstructure connection construction, the use of Ultra-High-Performance Concrete (UHPC) in the modular and other prefabricated superstructure element connection as a closure pour is highly recommended. This concrete can provide a highly durable and rapid construction. Due to its high strength, a small width connection is enough to connect modular units and members. However, the bridge owner may hesitate using the UHPC due to its high cost, proprietary nature, and other restrictions.

In the connection between superstructure and substructure, sometimes the use of full moment connections to emulate the cast-in-place connections is preferable. In this case, closure pour connection should be used that provides high quality, rapid construction, and better riding surface. If self-compacting concrete is used as closure pour, it can provide high homogeneity, uniformity and no need for vibration [47].

3.6 Categorization of Bridges based on Bridge Span

ABC aims to reduce the onsite construction time and activity. To that point, the use of modular systems in the bridge construction is preferable. Typically bridge designers categorize bride super- and substructures into 4 groups based on the bridge span as follow [47].

40 ft. < bridge span< 70 ft.

70 ft. < bridge span< 100 ft.

100 ft. < bridge span< 130 ft.

bridge span> 130 ft.

In a particular ABC project, the bridge span or girder spacing is normally selected based on the fabrication and shipping considerations, and vice-versa. For bridge span up to 130 ft., pre-tensioning method (without the need for post-tensioning) can be used in the site. If girders or superstructure modules are shipped to the site, and bridge span over 130 ft., post-tensioning technique needs to be used to extend the bridge span. However, it may be economical to add more piers to reduce the dead load in each pier, and to reduce the shipping weight of the bridge components. Also, it should be noted that facilitating the bridge construction with the use of lifting and crane-based fabrication has been reported normally to be the most cost-effective method [47]. However, this assessment may be valid if the time and speed of construction are not prohibiting factors. When prefabricated modular systems and bridge elements are fabricated near the site, it is possible to increase the girder spans over 130 ft.

3.7 Considerations for superstructure system and elements selection

There are different viable systems available to be considered as superstructure for the ABC projects. However, each system has its own advantages and disadvantages. Therefore, a superstructure system should be selected in such a way to meet the project goals, provide higher safety, and be constructed in minimum time. Also, a value analysis is needed to select the best economic system [31, 54]. The factors that should be considered in the selection of each superstructure system is summarized in Table 3-2 provides alternatives for superstructure element types and related considerations.

Table 3-2: Superstructure system selection considerations

Superstructure system	Comments
Precast concrete girder with separate partial-depth precast deck	-Lighter sections make the shipping easier or longer spans can be used. -Camber control is difficult. -Accommodates more variable geometry. -Cast-in-place top part of deck can provide a smooth riding surface. -The cast-in-place top part of deck needs additional construction time. -Longer time needed to open the bridge to traffic after construction due to curing time for deck.
Precast (full depth) decked concrete girder	- Decked slab girder is normally shallow and suitable for short spans - The girder lengths in decked girder could be limited by ultimate strength of the top of slab concrete and live-load deflection - The decked U-girder is a shallow and efficient, suitable for short- to medium-length spans of up to 144 feet. - The decked BT (bulb-tee) girder was developed to extend the span capability for standard decked sections. - The maximum span capability of decked BT girder when using live-load continuity for multi-span bridges is 195-feet. - Difficulties in accommodating transverse slope.
Precast concrete girder with separate full-depth precast deck	-Lighter girder sections make the shipping easier or longer spans can be used. -Camber control is difficult. -Accommodates more variable geometry. -Need additional time to place the deck. -Need additional access for deck placement. -Require additional depth and material for the girder top flange and haunch.
Precast concrete girder with full cast-in-place deck	-Accommodate more variation in geometry -Require additional time to form and case the deck -Worksheet, design aids, and its technology is widely available. -Longer time needed to open the bridge to traffic after construction due to curing time for deck.
Steel girder with full-depth precast deck	-Lighter girder sections make the shipping easier or longer spans can be used. -Camber control is difficult. -Smaller fabrication tolerances are needed. -Require deeper sections. -Availability of wide-flange sections may be an issue. -Requires close coordination between steel girder and concrete deck suppliers. -Horizontal shear design at the interface is critical.

	-Except for box girder, at least two girders are normally needed for each precast deck, affecting the section efficiency. -Normally, longer delivery time should be considered. -Steel sections are lighter compared to equivalent precast concrete.
Steel girder with partial precast deck	-Lighter sections make the shipping easier or longer spans can be used. -Accommodates complex geometry. -Smaller fabrication tolerances are needed.
Pre-decked steel girder including folded plate decked steel girder	-Lighter sections compared with pre-decked concrete girders make the shipping easier or longer spans can be used. -Coordination between deck and girder fabricator is needed. - Girders require additional step of painting or galvanizing - Additional work needed to accommodate complex geometry. - Difficulties in accommodating transverse slope.
Steel girder with full cast-in-place deck	-Better accommodates different and complex geometries. -More diaphragms/cross frames are needed in comparison with the precast deck. -Longer construction time is needed for forming and casting the deck.
Modular pre-topped concrete girder	-Accelerate the bridge construction -Improve durability and easier inspection -40 to 90 ft. span range
Precast I girder	-50 to 150 ft. plus span rage -Six AASHTO PCI standard sections can be used. Other standard sections are also available.
Precast bulb tee girder	-Increased efficiency in comparison to I shaped girder -Wide top flange increase stability for handling and shipping -Standard AASHTO PCI BT shapes should be used
Precast box beam	-Good for short to medium span range, 20 to 127 ft. -Adjusted box beams are connected using partial or full-depth grouted shear key connection
Full-width/Partial-width superstructure systems	-Depends on availability of space near the bridge site, transportation capabilities and construction/installation methods discussed in Section 3-2. - Depending on availability of nearby space, the superstructure system can be slid laterally or longitudinally in place or lifted by crane. -May range from a narrow transverse strip of bridge to the entire span. - Can also include miscellaneous elements such as railing. - May contain integral substructure elements.

3.8 Considerations for substructure system and elements selection

Bridge substructure includes pier, pier cap, and abutment systems that act as bridge elements that transfer superstructure loads to the foundation [31]. Pier caps are normally connected to the pier that is supported by the footing or pile cap. Piers can sometimes be constructed integrally with superstructure. In certain conditions, pier cap may be connected directly to the extended piles or foundation above the finished grade. Table 3-3 offers some alternatives and related considerations for substructure.

Table 3-3: Substructure system selection considerations

Substructure system	Comment
T-pier	Single column with a wide-enough cap that can support superstructure without the need for separate pier cap element
Open bent with separate pier and pier cap	To support wider superstructure Precast individually and connected at the site
Precast open bent	A combination of pier columns and cap precast together and installed at site. Accelerates bridge construction.
Column bent with web wall	Similar to above with advantages of wall piers.
Concrete Filled Tube column/pier	Allows greater design capacity
Pier cap with integrity details- Integral or semi-integral	Eliminate bearing and reduce maintenance Good for seismic area by integrating substructure and superstructure
Wall pier	Are used when the pier may be affected by the errant vehicles, and in rivers to prevent debris from collecting between columns
Abutment cap with integrity details- Integral or semi-integral	Better durability and load carrying capacity especially in seismic regions.
Abutment wall	Cantilever, stub, or spill-through types each with specific characteristics Can be designed in segments for easier shipping, and joined together at the site
Wing wall	Precast cantilever or modular precast
Beam seat or cap	Built with geosynthetic/reinforced soil or mechanically stabilized earth at the abutments.

3.9 Considerations for foundation system and elements selection

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4 Existing Bridge Replacement

According to the National Bridge Inventory data for bridges in the US in 2016, 9% of the bridges were in poor condition, 15% had service life older than average design life of the bridge, and 9% of them needed urgent strengthening or rehabilitation [55]. These data is indicative of the necessity of bridge maintenance, construction, and rehabilitation. One common method in improving the bridge performance is demolishing the existing bridge and construction of a new bridge. However, this method is expensive and is not a favorable option in urban areas where there is high congestion. New bridge construction can cause significant mobility and traffic problems. To address this issue, other options become more attractive that include retrofitting or strengthening of existing bridges, reuse, or partial replacement of existing bridges. To select the proper method to improve the life and performance of an existing bridge, a precise and comprehensive evaluation of existing bridges is needed. The bridge evaluation may well discover that some parts or subsystems of the bridge, such as foundation and/or substructure, are in good condition and only replacement of superstructure is necessary. The benefit of foundation and substructure reuse is the time and cost saving especially in urban and populated areas.

To accelerate the bridge construction, the reuse of substructures, let it be with some repair or modification, is favorable. In this case, the existing substructure must be inspected thoroughly and the best method to reuse the existing substructures is determined. The assessment of the existing foundation is a multidisciplinary task that needs geotechnical, construction, structural, and hydraulic expertise. The purpose of substructures assessment therefore is to provide enough information for decision making on the reuse of substructure.

An FHWA workshop in 2013 laid the foundation for evaluation means and methods for reuse of substructure and foundation for bridge replacement [2]. Figure 4-1 is an example guide for evaluation of the condition of substructure and foundation reported by this workshop [56].

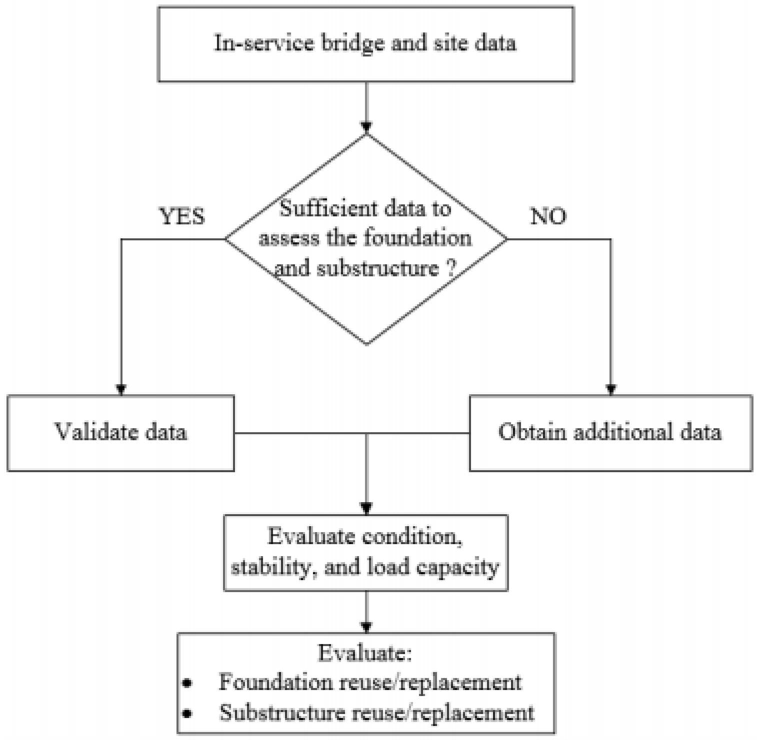


Figure 4-1: Example flowchart to evaluate the bridge condition [56]

According to the literature, the reuse of foundation and substructure have economic, social, and environmental impacts especially when the construction method for replacement of the rest of the bridge is accelerated. In this case, the use of Accelerated Bridge Construction (ABC) in replacement of superstructure and modification of substructure and foundation play an essential role to magnify the benefits of reuse. However, providing a proper evaluation of existing bridges for verifying their adequate performance and their remaining service life are the primary challenges. The NCHRP synthesis 505 identified the significant challenges in replacement of existing bridge as evaluating the current condition of bridges, the capacity of existing foundation and substructure, the remaining service life of existing foundation and substructure, and evaluation of foundation and substructure reuse [57]. These challenges determine the importance of foundation and substructure investigation.

The Federal Highway Administration publication on the "Foundation Reuse for Highway Bridges" has defined the reuse of bridge substructure or foundation as "use of existing foundation or substructure in whole or part, when existing bridge has been evaluated for new loads" [58]. FHWA definition for reuse of foundation includes reuse of substructure and foundation above and below ground, or rehabilitation of existing substructure and foundation when superstructure has been determined to be replaced or otherwise optimized by reduction of superstructure dead load with the use of lightweight elements or other methods. Also, the foundation reuse may occur when widening of bridges or strengthening and retrofitting of foundations are included among the options. Figure 4-2 shows four options introduced by the FHWA publication [3] that may arise when considering bridge replacement;

- Option 1, the existing foundation will be discarded, and a new foundation with new alignments will be constructed.
- Option 2, the existing foundation alignment will be kept, but a new foundation/substructure will be installed. In this case, the demolition of substructure will be needed.
- Option 3, the existing foundation will be reused with no or minor modification, strengthening, or retrofitting.
- Option 4, the foundation will be reused with some form of modification, retrofitting, or strengthening.

As described, Options 3 and 4 are foundation reuse.

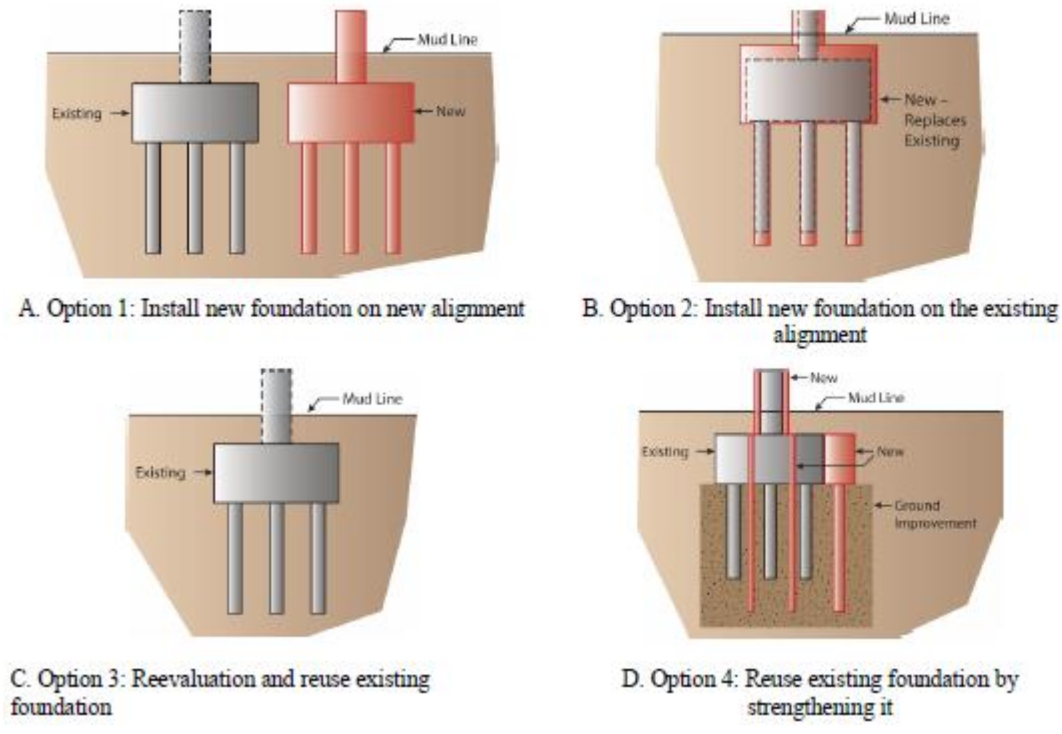
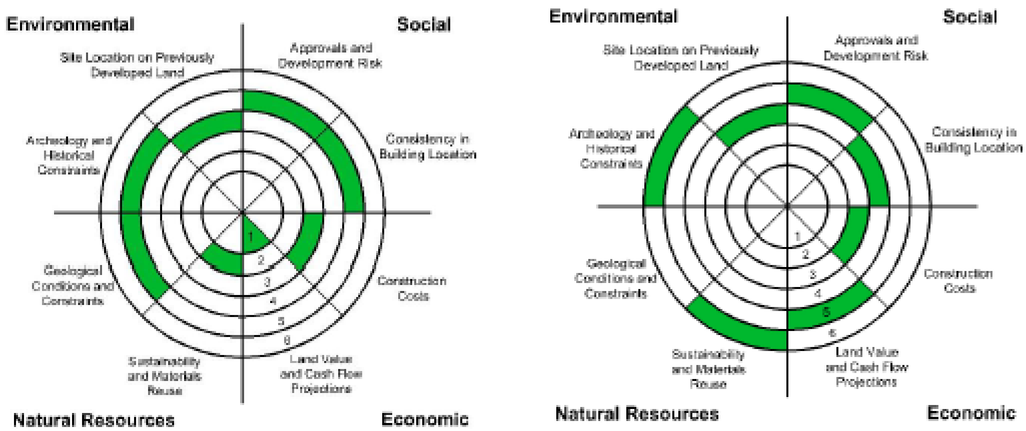


Figure 4-2: Foundation replacement and reuse options [58]

According to the Sustainable Project Appraisal Routine (SPeAR®) study, eight factors should be considered to decide whether reuse of foundation is an option [59]. These factors are;

- Site location,
- Archeology and historical constraints,
- Geological constraints and conditions,
- Material reuse and sustainability,
- Land value and cash flow,
- Construction cost,
- Consistency in location, and
- Risks.

Each of these factors can be rated from 1 to 7 (Figure 4-3). The lower value indicates the higher benefit in foundation reuse with respect to replacement. The charts developed for New York and Houston demonstrate that the reused of building foundations are more beneficial than replacement. However, factors need to be evaluated for reuse of bridge foundation benefits maybe different from building reuse factors. Figure 4-4, is a modified SPeAR chart for bridge foundation reuse [60]. These charts however leave out one important parameter that is the time required for construction. Benefits of reducing the time of construction can valuated in various means. Laefer and Farrell [60] included the time factor among motivations in reusing of bridge foundations that may differ from the building. The conducted survey identified the motivations and their rates shown in Figure 4-5. As shown, economic factors and accelerated construction are the highest rated factors that support strongly the use of ABC method in bridge construction [60].



A. New York City site B. Houston, TX site

Figure 4-3: Modified SPeAR charts for reusing of building foundations in New York and Houston [59]

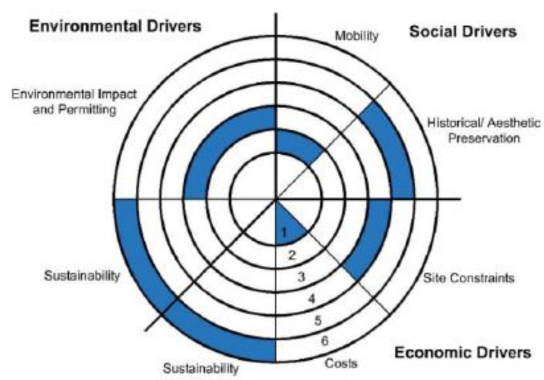


Figure 4-4: Modified SPeAR charts for reusing of bridge foundations [58]

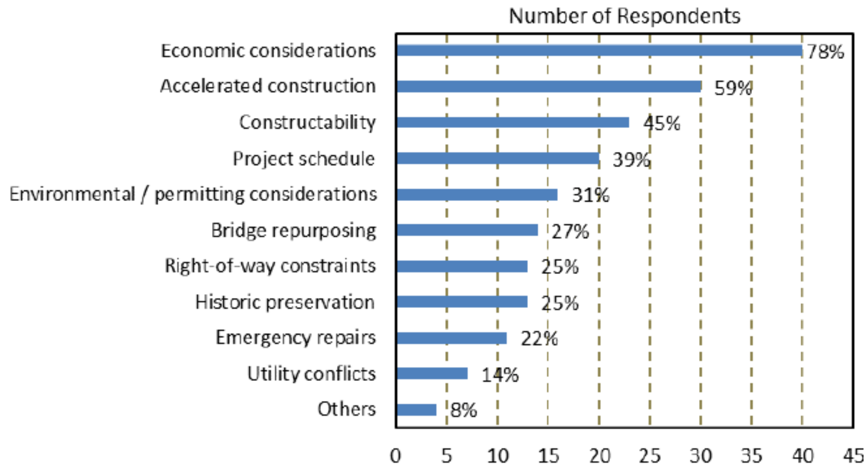


Figure 4-5: Motivations for bridge foundation reuse [58]

4.1 Type and Design of Existing Foundations

OU TO PROVIDE THEIR WORK FOR THIS SECTION

4.2 Evaluation of Existing Substructure for Potential Reuse

The critical issue in the reuse of bridge substructure and foundation is defining the remaining service life (durability) of the bridge components. Accordingly, to find if the reusing of bridge components are economical, one needs to perform a life-cycle cost analysis based on the remaining service life of the bridge elements. Therefore, an exhaustive bridge evaluation should be conducted to first determine the remaining service life of bridge components. The substructure components of bridges are wall piers, columns, abutments, wing walls, and pier caps. These elements can be constructed from reinforced concrete or steel.

During its service life, steel can be corroded if not protected properly. This corrosion can cause reduction in the cross-section of steel and consequently decrease the strength of steel elements. In the reinforced concrete elements, the reinforcements can be corroded or/and the concrete cover may be degraded. The corrosion of reinforcements and degradation of concrete cover are normally interrelated. For example, the concrete cover may initially cracks due to the loads, causing the penetration of corrosive agents into the concrete, and leading to corrosion of reinforcements, that in turn because of volume increase will damage the concrete cover further.

The durability and remaining service life assessment of bridge components is categorized in three stages as shown in Figure 4-6.

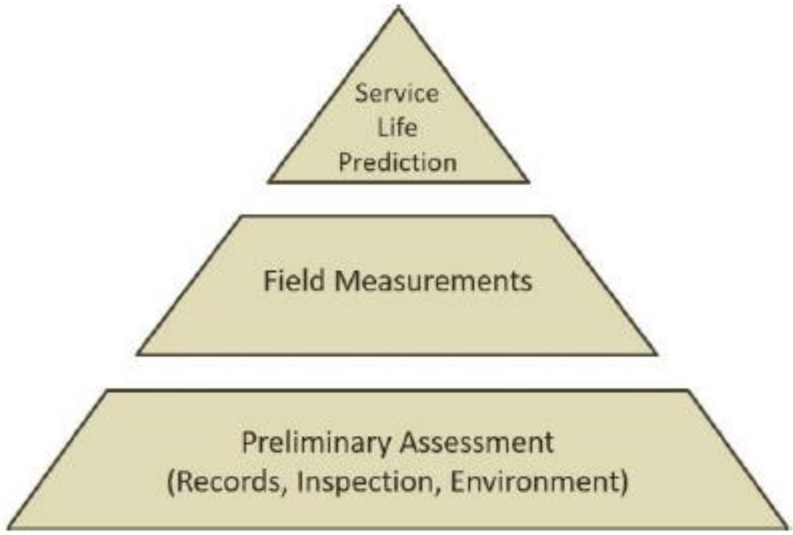


Figure 4-6: Durability and residual service life assessment of bridge substructure [58]

In the preliminary assessment, the previous performance issues, environmental conditions, and concerns related to the durability of a bridge are investigated. This assessment is playing an essential role in providing an appropriate plan for further inspections and tests as well as repair type and extent. The preliminary assessment and procedure are summarized in Table 4-1.

Table 4-1: Preliminary assessment procedure [58]

Evaluation Procedure	Reason/Outcomes
Records Review	Review of past inspection history allows for assessment of the time history of bridge performance
Environmental Conditions	Environmental conditions at the bridge dictate the types of deterioration expected. Important aspects to consider are: exposure to deicing salt, exposure to salt water, fresh water, contaminated soil or water, humidity, stray currents, or freeze/thaw conditions
Visual/Physical Survey	Document extent of cracking, signs of rust staining or efflorescence, erosion of concrete paste, and extent of spalling. Locate delaminated areas using hammer sounding and physical methods. Generally, overlaps with integrity assessment in finding the current condition of the concrete.

As shown in Table 4-1, a comprehensive review of previous records and a visual inspection is required in the preliminary assessment. Then, a plan is developed for further investigation through inspection and testing to provide the information required for determining the condition of bridges. Finally, a life-cycle cost analysis needs to evaluate the benefit of reusing of foundation and substructure.

According to the preliminary evaluation by considering observations and inspections, local experiences and conditions, and environmental conditions, a test plan can be developed to define the structural capacity of a bridge. In the test plan, the characteristics of bridge foundation, substructure, and bridge site should be considered. One example of site consideration is the level of water table that can cause different conditions for part of the pile over and below the water table. In the testing plan, various tests including visual inspections, physical inspection using nondestructive tests (NDTs), or dissection of removing defective portions and performing the tests can be considered. However, the testing plan is highly dependent on the type of bridge components that can be concrete or steel. In the following, the required tests for reinforced concrete and steel members are summarized.

4.2.1 Concrete Elements Field Testing

The aim of durability testing plan for reinforced concrete members is to identify the extent and depth of cracks, reinforcement's corrosion, extent of carbonation and chloride penetration into the concrete cover. The typical factors need to be evaluated to define the durability of concrete elements are summarized in Table 4-2. Also, the tests to be conducted to assess the concrete elements degradation factors are listed in Table 4-3.

Table 4-2: Field testing related to the concrete elements [58]

Available Testing	**Issue identified during preliminary evaluation**	**Notes**
Cover Measurement	Corrosion, chloride exposure, carbonation	Determine cover thickness important to evaluation of other durability issues.
Chloride Testing	Exposure to chlorides	Determine profile of chloride diffusion into cover concrete. Initial chloride testing can be limited to surface and depth samples, to ascertain the magnitude of bound and unbound chlorides
pH testing	Carbonation	Perform pH testing on extracted cores to determine depth of carbonation penetration
Half-cell potentials	Active corrosion	Perform half-cell potential testing in areas of suspected corrosion
Electrical Resistivity	Potential for corrosion	Useful for finding areas of corrosion or areas susceptible to corrosion

To evaluate a concrete element susceptibility to chloride, carbonation, corrosion, and other degradation substances, cover depth of concrete elements is needed to be measured [58]. It is possible to find the cover depth of an element from the drawing design plan. However, there are differences between the actual depth and design plan. Also, it is possible that the cover depth of element may change along with the length of element. In this case, the actual cover depth can be detected using ground penetration radar (GPR) or covermeters. These tests should be conducted in different parts of member length to define the rebar location and the minimum cover depth along the member length (Table 4-3).

Concrete cover cracks are primarily evaluated using inspection and recording the length, width, depth, and location of cracks. This inspection can be conducted repeatedly in time intervals to assess the progress of cracks. It is possible to determine water penetration susceptibility by efflorescence, and rust susceptibility by rust stains. Also, the sensitivity of concert cover delamination can be evaluated using standard ASTM D4580 by hammer sounding, steel rod off the surface, impact-echo, ultrasonic pulse responses, wall climbing robots, or infrared thermography tests [61, 58]. The purpose of finding the delamination location is to identify the corrosion susceptibility and areas with high porosity that can cause air penetration. The regions where corrosion is active can be detected using half-cell tests. To identify porosity of concrete elements, the 90-day ponding test or electrical methods should be used. Another concern is chloride ingress into the concrete. Electrical method is one type of identifying ingress susceptibility. Also, acid-soluble or water-soluble test are other methods that can be conducted on samples taken from suspect concrete. In the acid-soluble method, the bounded and unbounded chloride ions are measured. However, in water-soluble method only unbounded and free chloride ions are measured [58].

Another concern with the reinforced concrete members is air penetration and their susceptibility to carbonation. Carbonation can be detected on the surfaces of concrete with measuring lower ph. When a surface of concrete element is carbonated, air can ingress to the member. By penetration of air into the concrete cover, the carbonation effects extend toward the reinforcement, reducing the alkalinity of concrete and protection provided for steel. One way to test the carbonation susceptibility is evaluating the air penetration using SHRP-S-329 standard [58]. Another way is using phenolphthalein test which is a ph indicator. To perform this test, a core needs to be taken. When the phenolphthalein test shows the ph less than 9, the concrete is considered carbonated. When the carbonation is not significant, its effect could be ignored in the remaining serivce life analysis. However, service life modeling by considering the carbonation effect is necessary when the carbonation is substantial.

Furthermore, the common tests to evaluate the freeze/thaw damage is petrography test [58]. It should be noted that to estimate the cycle of freeze/thaw during the service life of a member, the temperature records from weather stations near the bridge can be used.

Table 4-3: Durability tests of concrete elements

		Comment
Cover depth	Ground Penetration Radar (GPR)	Radar reflection, Cover more area,
	Covermeters	Eddy current detection, Less affected by moisture and voids
Concrete cover delamination	hammer sounding, steel rod off the surface, impact-echo, ultrasonic pulse responses, wall climbing robots, infrared thermography	Delamination survey, ASTM D4580

Corrosion	Half-cell	Location of corrosion ASTM C876
Porosity	90-day ponding test	AASHTO-T-25
Chloride ingress	Electrical method	ASTM C1202
	Acid-soluble test	ASTM C1152
	Water-soluble test	ASTM C1218
Carbonation Susceptibility	SHRP-S-329	Air permeability CO^2 ingress resistance
	phenolphthalein test	Ph indicator
Freeze/Thaw	Petrography	
	Temperature measurement	

Furthermore, the commonly used NDT technics for concrete elements are summarized in Table 4-4. As shown, these are the Ground Penetration Radar (GPR), Ultrasonic Pulse Velocity (UPV) and tomography, infrared thermography, Electrical Resistivity (ER), radiography, rebound hammer, Impact Echo (IE), Spectral Analysis of Surface Waves (SASW), Sonic Echo (SE), Impulse Response (IR), Bending wave, and Ultraseismic (US).

Table 4-4: NDT technology for concrete elements

NDT Method	Issues Investigated
Ground Penetrating Radar	Rebar layout, voids, cover depth
Ultrasonic Pulse Velocity and tomography	Location of voids, weak zones, honeycombing, and cracks
Infrared Thermography	Location of voids and delaminations
Electrical Resistivity (ER)	Presence of water, chlorides, and salts
Radiography	Location of voids and condition of tendons and strands
Rebound Hammer	Surface strength of concrete
Impact Echo/Ultraseismic/Parallel Seismic	Location of defects and voids in piles

4.2.2 Field Testing for Steel Elements

Most of steel member evaluation is based on physical assessment and inspection that are conducted periodically. When field evaluations for steel members or portion of them that are underwater or underground is performed, test pit excavation is needed to drive a core and evaluate the exposure of steel members directly. Care should be taken not to damage the foundation during excavation and coring [58].

The critical points of steel members that are highly susceptible to corrosion are parts in the water line or below the pier cap. In corrosion evaluation, the rusted product should be removed to assess the corrosion rate. The corrosion rate is defined based on the initial size of a section and remaining steel during the service life of the member. Due to that, periodic inspection should be conducted to define the corrosion in each interval to determine changes in corrosion rate.

Furthermore, the commonly used NDT technology in steel elements to detect flaws are Dye Penetration Testing (PT), Magnetic Particle Testing (MT), Eddy Current Testing (ECT), Ultrasonic Testing (UT) and Phased Array Ultrasonic Testing (PAUT), and Acoustic Emission (AE) [58]. The usage of these technologies is summarized in Table 4-5.

Table 4-5: NDT technology for steel elements

NDT Method	Comment
PT	Detect cracking and surface flaws
MT	Detect surface breaking cracks
ECT	Detect flaws, material, and coating thickness
UT and PAUT	Detect surface and undersurface flaws
AE	Monitor cracks growth

4.2.3 Structural capacity

The structural capacity of foundation and substructure of bridges are assessed based on the durability and integrity evaluation and is required to ensure safety and capacity for reusing them in the construction of a replacement bridge. The capacity assessment of bridges determines the available capacity of foundation and substructure and follows the updated AASHTO LRFD standard and state DOT guideline [58]. It should be noted that the design code may have been updated and changed since the original design for existing bridge was performed. Also, there might be some misinformation from the design detail of the bridge in the past that should be verfied during the integrity assessment. More importantly, changes might have occurred during construction (not recorded on as-built) of a bridge that warrants the field testing and inspection to determine the current state and condition of bridges.

In the structural capacity assessment, the following should be addressed [3]:

- Verifying the original design capacity
- Determining LRFD capacity for foundation originally designed using ASD or LFD
- Determining if increased nominal capacity is available
- Determining whether the capacity has been reduced due to deterioration

In this manner, it can be determined if the capacity as readily adequate for reuse, or strengthening and repairs are needed to raise the capacity. The important aspect of capacity assessment is also defining the extent of strengthening and retrofitting. To address this issue, the following questions should be addressed. How the design code changed, new loads on the foundation and substructure, changes in material properties and structural capacity of elements, changes in the geotechnical capacity of bridges, and finally defining the effect of expectred changes on the capacity [58]. By answering these questions and issues, it is possible to determine the potential for reusing of bridge substructure and foundation. The structural capacity should be determined through analysis of the bridge structure as a whole and the foundation and substructure for the purpose of investigating the reuse.

An important aspect of performing analysis and capacity assessment is defining the future loads on bridges. The future loading of bridges may change or stay the same. The changes in live and dead loads of bridges can occur due to a widening of a bridge, the use of a new superstructure, the potential of extreme hazards, or use of new materials. The summary of possible changes in the bridge loads is listed in Table 4-6.

In the modeling and analysis of bridge to evaluate the potential for reusing the existing bridge components, the structural capacity of the bridge elements should be assessed. The pier column, wall piers, pier cap, and abutments are the elements in the substructure of bridges, and their capacity and functionality should be evaluated for their reuse.

In addition to vertical loading, a critical loading for the pier column and pier wall is the lateral loading that creates moments in the element. According to the AASHTO design specification, the lateral loading can be induced from a seismic event, vessel or traffic collision, ice or debris, wind, or construction consequences [62]. Thermal variation can also generate lateral loading on substructure. These loads can make tensile stress in the elements and create cracks in the portion of elements that are in tension. Another reason for cracks could be corrosion of rebar in the elements. According to the Service Limit states of AASHTO standard specification section 5.4.2.6, in the capacity evaluation, the emphasis should be to prevent the occurrence of tensile stress instead of providing for a higher modulus of rupture [62]. In Strength Limit states evaluation for extreme event limit case, the rupture modulus should be used when there are no significant cracks in the tensile portion of the elements. Other loads due to the construction like traffic rerouting, bridge sliding, demolition, ground movement, and construction equipment loads also need to be considered.

Table 4-6: Possible changes in the loading of a bridge for potential reusing [58]

Possible Causes of Additional Loads	Possible Causes of Reduced Loads
Wider/heavier superstructures	Lighter Superstructure (lightweight concrete, more efficient design)
Reduction in number of Piers (increased span length)	Increased number of piers (decreased span length)
Higher wind loading due to new analysis or superstructure cross section	Better wind profile, changes to later behavior
Higher seismic loads	Reduced superstructure mass resulting in lower seismic forces
Higher hydraulic/scour loads due to structural changes, new design floods/codes, or improved analysis	Scour countermeasures, new structural systems to take hydraulic loads
New design collision/impact loads	Installation of fenders, dolphins, or pier protection
Increased number of lanes	Reduced number of lanes
Heavier vehicles	Reduced soil pressures (better analysis, replacement of backfill with lightweight fill such a geofoam, changes to soil geometry)

Abutment and wingwall can experience settlement, horizontal movement, rotation, and slope stability problem. The excessive movement of walls can make the wall unable to support the soil and surcharge loads at rest condition of the wall. When the wall moves, the wall is in an active state that causes a reduction in the lateral pressure coefficient. This reduction causes reduction in pressure loads to the wall. However, to reach the active state of a wall, a minimum amount of wall movement is necessary. The required amount of movements are specified in section C3.11.1-1 of AASHTO standard specifications [62]. Conversely, by movement of walls, the soil in front of wall is in the passive state. In passive state, the coefficient of earth pressure increases compared to the at rest state and prevents movement of the wall. Since in the active state of the wall the coefficient of earth pressure decrease, a safety factor higher than 1.5 should be considered. When the wall is in the at rest state, a safety factor of 1.35 should be used. It should be noted that to define the state of a wall, a proper estimation of wall movement is needed to determine actual pressure to the wall.

Pier caps generally experience shear and flexural demands. The transverse and longitudinal reinforcement of these elements should be evaluated prior to performing capacity analysis due to their essential function in the element capacity. The transverse (shear) rebar are more prone to corrosion because they are closer to the face of the elements. To perform capacity analysis, the strut and tie analysis should be conducted according to the section 5.6.3 of AASHTO LRFD design specification [62]. Flexural and shear reinforcements simulate as ties in the strain and concrete simulate as struts.

4.2.3.1 Modeling and Analysis

Different approaches of modeling and numerical simulation is used to determine the forces, moment, and stresses that a bridge structure experience, including determination of loads that the substructure/foundation should carry. The available methods are listed in Table 4-7. As shown, for purposes of approximate analysis, Finite Element (FE) analysis, p-y curve, and wind tunnel testing can be carried out to identify the behavior of structures [58].

Table 4-7: Modeling methodologies for bridge structures [58]

Modeling Methodology	Advantages	Disadvantages	Notes
Approximate analysis	Simple, based on basic engineering knowledge, finds forces/moments in the substructure elements	Cannot account for non-linear soil contributions, or complex geometry	Generally good as a first estimate of loading on the structure and soil. Can be difficult to account for behavior of soil.
Finite element analysis	Allows input of entire system, including soil and wind, can be non-linear, allows input of structure to help determine actual forces going into substructure elements	Can be computationally expensive for large bridge, may require many hours of input, requires knowledgeable staff to create model, requires knowledge or estimation of many material properties	FEA models can be of entire bridge system, or individual substructure elements. Can include non-linearities if needed, although at increased model complexity.
P-y curves (and T-Z, T-Θ, Q-Z)	Simplistically includes soil behavior, can be applied to FEA models, reduces computational cost while approximating soil behavior	Requires experience, difficult to apply to large diameter piers in deep soil	Simplifies input of soil behavior through non-linear springs. Linear springs can be used if they appropriately approximate the soil behavior in the load case being considered.
Wind tunnel testing	Accurate estimation of wind forces acting on superstructure and substructure	Expensive, time consuming	Allows determination of wind forces transferred to substructure using scale models. Generally, only used for signature bridge with unique profiles and complicated wind analysis.

4.2.4 Functional adequacy

The decision regarding demolition, replacement, or rehabilitation of an existing bridge should be conducted according to the structural capacity and functional adequacy of the bridge. The improvement needs for existing bridges should be determined according to the functional adequacy and structural safety. Engineering analysis for structural safety is performed to support the structural design requirements. While the bridge may be structurally sound, it may be functionally obsolete or poor. The term "Functionally Obsolete" or "Poor" condition is defined by FHWA [https://www.fhwa.dot.gov/bridge/britab.cfm] as:

This term was previously defined in https://www.fhwa.dot.gov/bridge/0650dsup.cfm as having an appraisal rating of 3 or less for Item 68 (Deck Geometry), Item 69 (Underclearances), or Item 72 (Approach Roadway Alignment), OR having an appraisal rating of 3 for Item 67 (Structural Condition) or Item 71 (Waterway Adequacy). Functionally obsolete is a legacy classification that was used to implement the Highway Bridge Program, which was discontinued with the enactment of MAP-21. As such, we encourage the use of the Good-Fair-Poor bridge condition measures outlined in the Pavement and Bridge Condition Performance Measures final rule, published in January of 2017.

In such cases (i.e., functionally obsolete or poor), improvements and modifications may be required to upgrade the bridge functionality including elevating or widening by considering current and future needs. Factors to be considered for bridge functionality includes roadway width, clear height (over and under-clearance), and waterway adequacy.

FHWA has provided other guidelines to determine bridge dimension and geometry, functional description, and evaluating bridges conditions [63]. State DOTs have their own guidelines for evaluation of bridge conditions. As an example, Florida DOT provides its structural design guideline and the requirements for bridge widths and geometry. An example is shown in Table 4-8.

Table 4-8: Minimum width for existing bridges [64]

Bridge Median Treatment	Minimum Width		
	Traveled Way Width	Shoulder Width (ft)	
		Median	Outside
Undivided (AADT < 750)	Total Width of Approach Lanes	n/a	2.0
Undivided (AADT ≥ 750)	Total Width of Approach Lanes	n/a	4.0
Divided (Median Separator)	Total Width of Approach Lanes	1.5	4.0
Divided (Median Barrier Wall)	Total Width of Approach Lanes	2.5	4.0
One Way Bridges	Total Width of Approach Lanes	2.5	4.0

4.2.5 Integrity and remaining service life

The geotechnical and structural stability and integrity check for bridge components are required to assess for potential reuse. The assessment and evaluation can be conducted using visual inspections, testing on the samples, performing NDT tests, and taking cores from the existing components and conditions. The main issue in the integrity of a bridge is deterioration of components due to their exposing to the environment during their service life. This issue can cause decrease in the capacity of components.

The bridge components were generally designed based on the day the bridge was constructed using the predicted conditions and loads through the Load and Resistance Factor Design (LRFD) standard method or the applicable code at the time of design. Also, in the construction of bridges, proper QA/QC may not have been applied. Additionally, changes in design code might have occurred compared to the time when bridge was originally designed. In fact, in redesigning the existing bridge, the confidence in initial construction and design quality in addition to the current condition should be considered. Therefore, a comprehensive and precise integrity evaluation of bridge is essential with the use of the material properties, deterioration effect in the capacity of components, damages occurred to the components, and changes in the soil system and stability. To address these factors, all members of the bridge should be evaluated along with the geotechnical issues [58]. Figure 4-7 illustrates the required integrity assessment steps for components of bridges constructed from concrete or steel [58]. The integrity assessment of steel and concrete components are reviewed in this section.

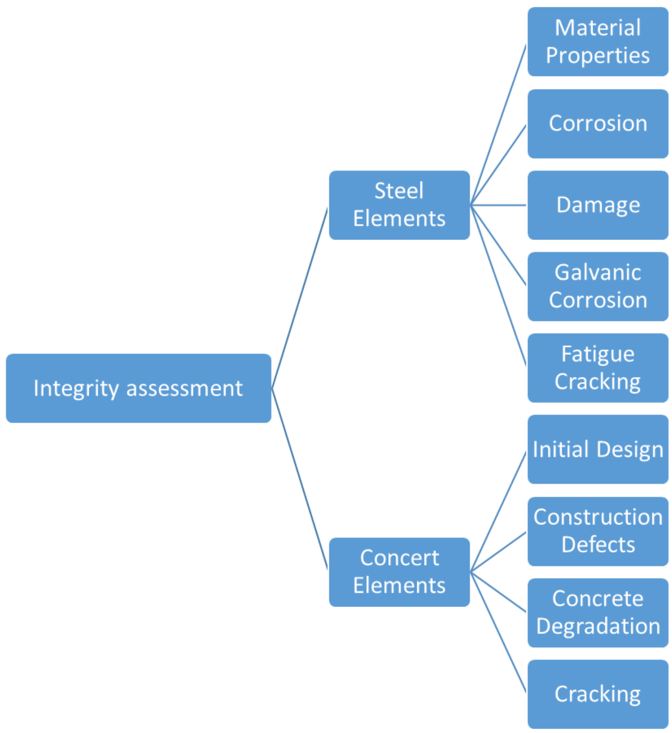


Figure 4-7: Aspects of Integrity assessment [58]

4.2.5.1 Integrity of concrete elements

The reinforced concrete is commonly used in the construction of pier wall, abutment wall, column, pier cap, piles, and shafts. Since concrete can bear very low tensile strength, the reinforcing bars are used in the concrete elements to increase the tensile strength of the elements. Concrete can provide compressive strength and cover for rebar to prevent corrosion. Cracks in concrete can expose the rebar and cause corrosion. In fact, the rebar corrosion is the main control factor for the service life of the concrete elements. This factor was discussed in the evaluation of service life of reinforced concrete. Another aspect of concrete elements is integrity evaluation. Concrete elements integrity assessment is summarized in Table 4-9 and includes, initial design, construction defects, degradation, damage, and cracking of concrete elements.

In the initial design assessment, the mix properties, reinforcement layout, compressive strength, and reinforcement strength are evaluated. Mix properties of concrete elements include water/cement ratio, aggregate classifications and properties, entrained air in the concrete, etc. To assess the compressive strength of concrete elements, generally, the unconfined compressive tests should be conducted. However, the NDT technology can be used to verify the properties, detect defects or ensure the integrity of the concrete element. In reinforcement layout assessment, the size of rebar, lap splice length, and all the aspects of reinforcement placement are evaluated using ground penetration radar (GPR), radiography, or covermeter test. The reinforcement strength can also be determined using design drawing details and tests on the samples taken from the members.

Defects and issues left during construction may include honeycombing, forming of weak zones, cold joints, and voids in concrete elements. In honeycombing, the improper mixing of aggregate with cement due to insufficient or poorly sized aggregates causes lower strength in member and formation of paste bonding. Weak zones are also initiated due to improper mixing of aggregates and higher w/c ration that leads to lower compressive strength. In large elements like pier caps, the pouring of concrete may be performed in several steps that normally results in cold joints and discontinuities plane between sections. The other problem is in formation of voids around rebar due to insufficient fluidity of concrete resulting in decrease in capacity of members.

The concrete degradation and damage that affects long-term concrete quality and durability include freeze-thaw damage, alkali-silica reactivity (ASR), delayed ettringite formation (DEF), external sulfate attack, paste erosion, calcium leaching, and fire damage [58]. In freeze-thaw damage, the trapped water due to improper mix design freeze and expand. The existence of high level of ASR can cause durability and integrity problems for concrete elements. This damage can be detected using photographic analysis in the form of gel formed in concrete. DEF which is due to poor construction technique can cause expansion and cracks in concrete. This issue also can be detected by photography. The dissolved sulfate in water can damage the submerged concrete elements. Paste erosion is another damage that occurs in the exterior face of elements and cause declares in load caring capacity of elements. Calcium leaching is due to infiltration of water into cracks and causes loss of paste inside the element. Fire also can damage the concrete elements by creating large cracks and buckling of rebar. This damage can be detected by evaluating the rebar layout using covermeter or GPR method.

Cracking that is one of important factors in the integrity assessment of bridges can be caused by shrinkage, change in temperature, flexural and shear forces, ASR, DEF, foundation movement, seismic effects, and corrosion [58]. Cracking due to shrinkage, ASR, DEF, and freeze-thaw are representative of problems in mix design of concrete. Structural cracks due to flexural and shear loads forms in tensile areas. Substantial structural cracks are representative of elements overload. Foundation movement can also cause tensile stress in concrete element and cracking. Seismic loads can also cause cracks. Corrosion of rebar accompanies increase in volume of rust product and creates cracks in concrete cover.

Table 4-9: Concrete elements integrity assessment

Concrete elements integrity	Aspects	Comment
Initial Design	Mix properties	W/C ratio, aggregate details porosity, etc.
	Compressive strength	Unconfined compressive strength Test to ensure strength Core test or NDT tests
	Reinforcement layout	Bar size, lap splice length, transverse reinforcements, GPR, radiography, or covermeter tests
	Reinforced strength	Detail from design drawing or perform test on samples removed
Construction issues	honeycombing	Mixing problem, poorly sized aggregate, decrease in paste bonding
	Weak zones	Improper mixing, higher w/c rate, lower compressive strength
	Cold joints	Discontinues plane
	voids	Flowing of cement around rebar, decrease in nominal capacity of element
Concrete degradation and damage	Freeze-thaw	Trapped water freeze, expand water in element
	ASR	Sufficient ASR cause durability and integrity problem
	DEF	Cause cracks, poor construction quality
	Sulfate attack	Submerge elements problem
	Paste erosion	Exterior face erosion
	Calcium leaching	Loss of cement paste
	Fire damage	Cracks, buckling of rebar
Cracking	Early age cracking	Cracks during curing process
	ASR, DEF, freeze-thaw	Cracks due to improper mix design
	Flexural and shear cracks	Initiated in tensile area of members
	Foundation movement	Create tensile stress
	Seismic events	Create ground movement and overload
	corrosion	Rebar corrosion

4.2.5.2 Integrity of steel elements

The concrete elements integrity assessment summarized in Table 4-10. Design drawing can provide enough information about different aspect of steel elements including yield and ultimate strength. However, if there is uncertainty about the design drawing report, the yield and ultimate strength of sections should be obtained by testing. Corrosion is another factor that can provide durability and capacity problem for steel elements. Corrosion usually occurs in elements that are located underwater or in wet conditions. Wet-dry zones usually exacerbate the corrosion problem. The amount of loss due to corrosion and the location of corrosion is an essential factor in integrity assessment. Galvanic corrosion is another type of corrosion that occurs in underwater elements or under the pier cap where two metals connect to each other [65]. Another integrity aspect of steel elements is evaluating the damages and overloads due to impacts and seismic events that can cause residual stress in elements. Also, the locations that experience tensile and shear stress like joints and connections may have long term and fatigue cracking problem that should be evaluated for integrity assessment. These issues can affect negatively the reuse potential of the substructure elements.

Table 4-10: Concrete elements integrity assessment

Steel elements integrity	Aspects	Comment
Material properties	yield and ultimate strength	Design drawing information, Test for uncertainty
Corrosion	Capacity problem	Where and how much corrosion, in wet areas
Galvanic corrosion	Capacity problem	Where two metals connect to each other
Damage	Permanent stress	Seismic loads
Fatigue cracking	Prone to failure	Shera or tensile stress in connections

4.2.6 Hydraulic issues

The changes in the hydraulic condition of bridges can induce or change the loads to the existing bridge substructure and foundation during its service life, and their impacts should be considered when reuse option is being considered. These changes may impose certain loading to the bridge never experienced in the past. The hydraulic changes can be related to rise in the sea level or precipitation. Hydraulic changes may also stem from changes in the code, such as consideration of a different flood return period. Aside from changes in the hydraulic loading, bridge scour is the main consideration for damages to the foundation and changes in the loading [58].

The LRFD design specification (AASHTO) states that the consequences of design flood for scouring must be considered for substructure and foundation of bridges [66]. The design flood is maximum of a stream flood event in 100-year return period or flood with an annual probability of 1% exceedance in a 100-year. The impact of scouring due to flood must be analyzed with full traffic loads on bridges and compared with check flood. The check flood is 500-year flood or flood with an annual probability of 0.2% exceedance. For this evaluation, the HEC-18 FHWA report can be used [67, 68].

The three types of scour involve changes in a riverbed, contraction scour, and local scour. The long-term changes in the riverbed are due to aggradation or degradation which depends on deposition or removal of sediments from the riverbed [67]. This change is caused by the hydrological condition of the river and not related to the bridge. Contraction scour occurs when the water velocity increases due to decrease in the channel width. The local scour occur near foundation where the stream causes vortices. The vortices occur when the regular stream is obstructed. This obstruction creates a high-velocity stream that can run the sediment [58].

4.2.7 Seismic considerations

The seismic evaluation of a bridge structure is conducted using C/D (capacity/demands) ratio. When this ratio is over or equal to 1, it shows that the element and structure have sufficient seismic capacity to resists seismic displacement and force [58]. The demands consist of displacement demand and force/moment demand. The displacement demand is evaluated using pushover analysis by considering the nonlinear behavior of materials and elements to define the ductility of bridges and elements. The force/moment demand estimates the actual forces and loading that the bridges and elements experience.

In a seismic event, the bridge element should be allowed to deform to absorb energy and prevent collapse. Allowing the plastic hinges to develop in a member controls the level of load applied to the structure. To evaluate this nonlinear behavior of elements, the pushover analysis is normally performed [58].

In the case of reusing the bridge components, the maximum considered event (MCE) should be used to define the maximum damage to the bridge. There are different methods to perform seismic demand analysis which depends on the bridge detail, magnitude of a seismic event, and importance of bridge. The detail of demand and seismic capacity evaluation of bridges can be found in the AASHTO standard specifications for LRFD seismic bridge design [66].

4.2.8 Other Considerations

Other consideration and hazards that should be considered in evaluation of existing bridges for potential reusing include wind loads, impacts loads, fire damages, ice and debris flow, and blasts. These potential hazards need to be considered depending on the condition and location of the bridge.

Wind load generally impact the superstructure and pier and cause lateral and moment loads in the foundation of bridges. Wind loads have two levels of operational and extreme impact. In operation impact level, the wind speed is considered to be 55 mph and impacts to the bridge with regular traffic. In an extreme level, the speed of wind depends on the location of bridge. Also, the change in climate should be considered during the time that the bridge designed and the time that it is evaluated for potential reuse. The climate change may make changes in maximum wind speed and return period. The required evaluation to assess wind impact to the bridge can be conducted using AASTO specification provision through LRFD standard specification [62].

The effect of impacts from vehicles and marine vessels collision on the bridge foundation and substructure has been considered in new design code. For this analysis, the performance-based analysis can be used to evaluate the truck collision impact on the piers [69]. In the case of marine vessel collision impacts, the AASHTO LRFD standard specification can be used to assess the vessel collision impact on bridge columns and foundation [62].

Burning underneath a bridge overpass can have adverse effects on the bridge component strength. The burning may cause weakness of steel rebar in the concrete elements. This weakening can produce cracks in the elements. To evaluate the effect of burning on the bridge components and identify the repair methods, the NCHRP report 12-85 can be implemented [70].

In case of considering the effect of ice and debris flow impact on the bridge piers and abutments that can produce lateral loads to the foundation, The NCHRP 445 can be used [71]. Also, to perform an analysis to assess the capacity of members due to the debris impact, the standard AASHTO specification can be used [62].

The loading due to the potential blasts and explosion are new and need to be evaluated. To evaluate the blasts effects and induced loads to bridges, the bridge design security manual provided by FHWA can be used [72]. Also, NCHRP report 645 provides a guideline to perform an analysis and identify the blast hazard into the bridges [73].

4.2.9 Remaining Service Life Analysis

Current condition and "State" of the substructure and foundation can be evaluated using the durability and integrity assessment as described above. Next step is to determine how the condition will be changed during the anticipated service life. This determination is critical in life-cycle-cost analysis and decision making on reuse, repair or replacement strategies for substructure and foundation. There have been several models developed to predict deterioration of construction material and geotechnical formation. More detailed discussion is included later in the section titled "Life-Cycle-Cost Analysis."

4.3 Evaluation of existing foundation for potential reuse

4.3.1 Structural capacity

NDE

Field Testing

Modeling and Analysis

4.3.2 Functional adequacy (width, height, traffic, etc.)

4.3.3 Integrity and remaining service life

4.3.4 Hydraulic issues

4.3.5 Seismic considerations

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4.4 Suitability of Substructure Types with Respect To Superstructure and Bridge Configuration

Suitability can be defined as having the structural load bearing capacity and at the same being compatible. Compatibility refers to geometric and design consistency. For example, for the substructure to be suitable for receiving the superstructure, it has to have adequate structural load bearing capacity to transfer the loads from superstructure to the foundation. At the same time, the substructure must be able to accommodate the superstructure geometry by width, height and alignment. For example, the width of superstructure, at the minimum by its bearing footprint, shall be enveloped by the substructure. Furthermore, the substructure design and detailing shall accommodate as designed connection to superstructure. For example, if the superstructure design prescribes an integral abutment or pier connection, the substructure shall be able to provide for the establishment of such connection in its detail. If any suitability requirements is not satisfied by the current condition of the substructure, modifications, rehabilitation, and/or retrofitting shall be performed on the substructure to make it suitable for superstructure. Another way to provide for suitability is to revise the design of the superstructure to be able to make it suitable for the existing substructure (e.g., use lighter deck elements). The decision on which of the two approaches are chosen to provide for suitability should be made with economical (time-cost) and structural considerations.

Flowchart in Figure 4-8 shows the process with which the substructure suitability can be checked against the superstructure.

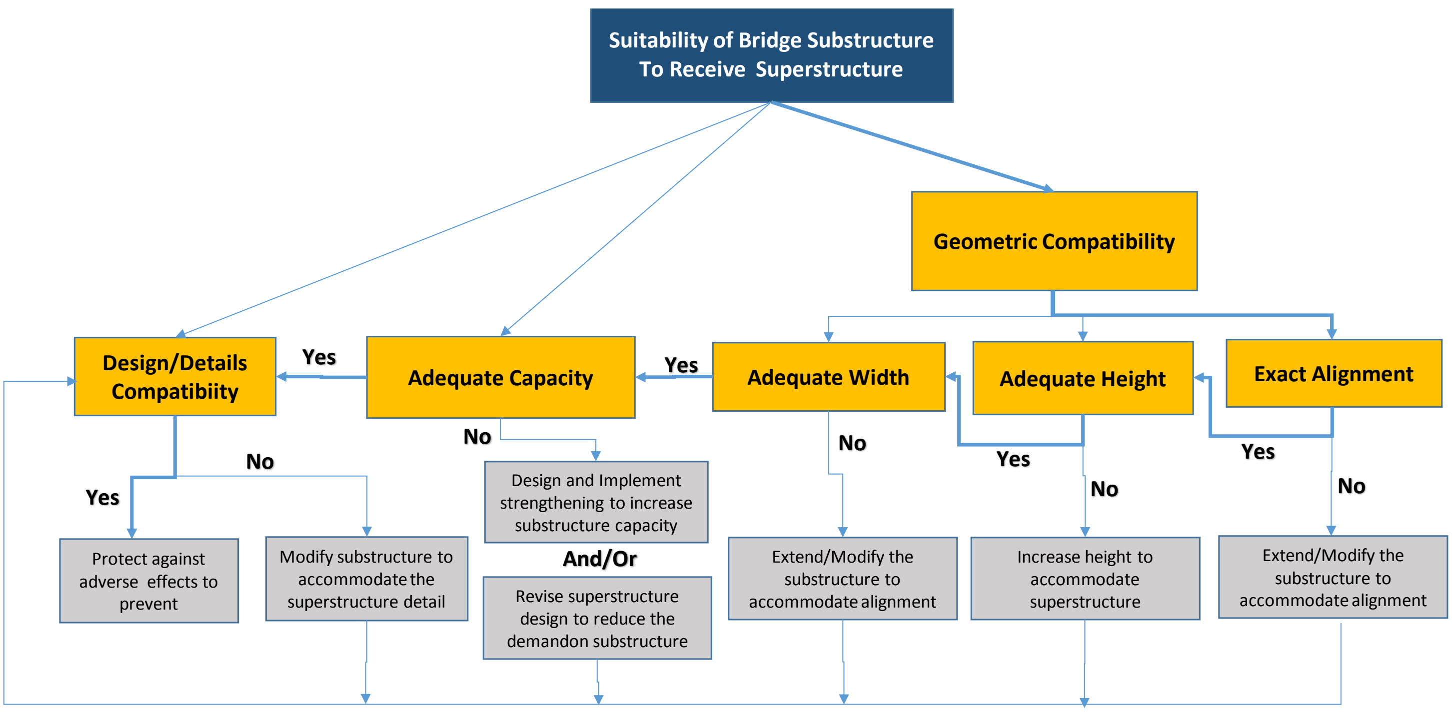

Figure 4-8: Factors effecting in the selection of existing bridge components

4.5 Suitability of Foundation Types with Respect To Superstructure/Substructure and Bridge Configuration

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4.6 Decision Making for Replacement, Reuse, Or Retrofitting/ Strengthening of Existing Foundations and Substructures

Decision on whether to reuse with or without modifications and strengthening or replace substructure and/or foundation is eventually an economic consideration let it be with various level of social and political considerations. The owner needs to decide the option that best serves the public and in general the users. This can be facilitated with the help of life-cycle-cost analysis taking into consideration all feasible strategies for addressing the problem in hand. Life-cycle-cost analysis calculated the cost associated with each strategy and tells the user which option provides the least cost over the time period considered in the study. Although it is not always easy to associate cost to every factor affecting the decision, but recent attempts to monetize various items such as user costs have produced valuable information that can be included in the analysis. Furthermore, risk-based analysis methods have been able to account for risk and therefore cost associated with uncertainties and probabilities. An example of such approaches is included in the next section. There has also been other attempts to develop tools and guidelines to facilitate the decision making. Some are described below.

SHRP 2 R02 research group at Iowa State University developed “GeoTechTools” to provide the available technology and methodology for reusing and replacing of existing bridges according to the condition evaluated for a bridge and predicted future demand. This web-based tool can be used to select the best option for reusing, replacing, or strengthening of existing bridges.

Also, some methods have been developed by European organizations to decide on reuse, retrofit, strengthening, or replacement of existing foundation. A procedure developed for decision making related to deep foundation for buildings is shown in Figure 4-9 [21]. As shown, compatibility of foundation with the substructure/superstructure plays an important role in this decision making. Furthermore, the evaluation, performance and cost analysis of existing foundation help to determine the potential for reuse of substructure.

Based on analysis of literature on available means and methods, the current research study has identified a general step-by-step procedure to assist the owners and consultants in their decision for reuse or replacement of substructure and foundation in ABC projects. Figure 4-10 shows a flowchart developed accordingly in this study that can be followed to determine whether retrofitting, strengthening, reuse, modification, or replacement of bridge substructure and foundation is a viable option. According to this flowchart, at first, the durability and integrity of the substructure and foundation is to be assessed followed by structural capacity estimation. Then, based on the capacity analysis, a life cycle cost analysis is to be conducted to evaluate the benefits of reusing the foundation and/or substructure. The life cycle cost analysis should be able to determine the optimum strategy for repair, retrofit, rehabilitation, modifications, or replacement that is economically and structurally justifiable. Durability, integrity and capacity evaluations were described above. The next section explains the basics of life-cycle-cost analysis in general terms for bridge construction.

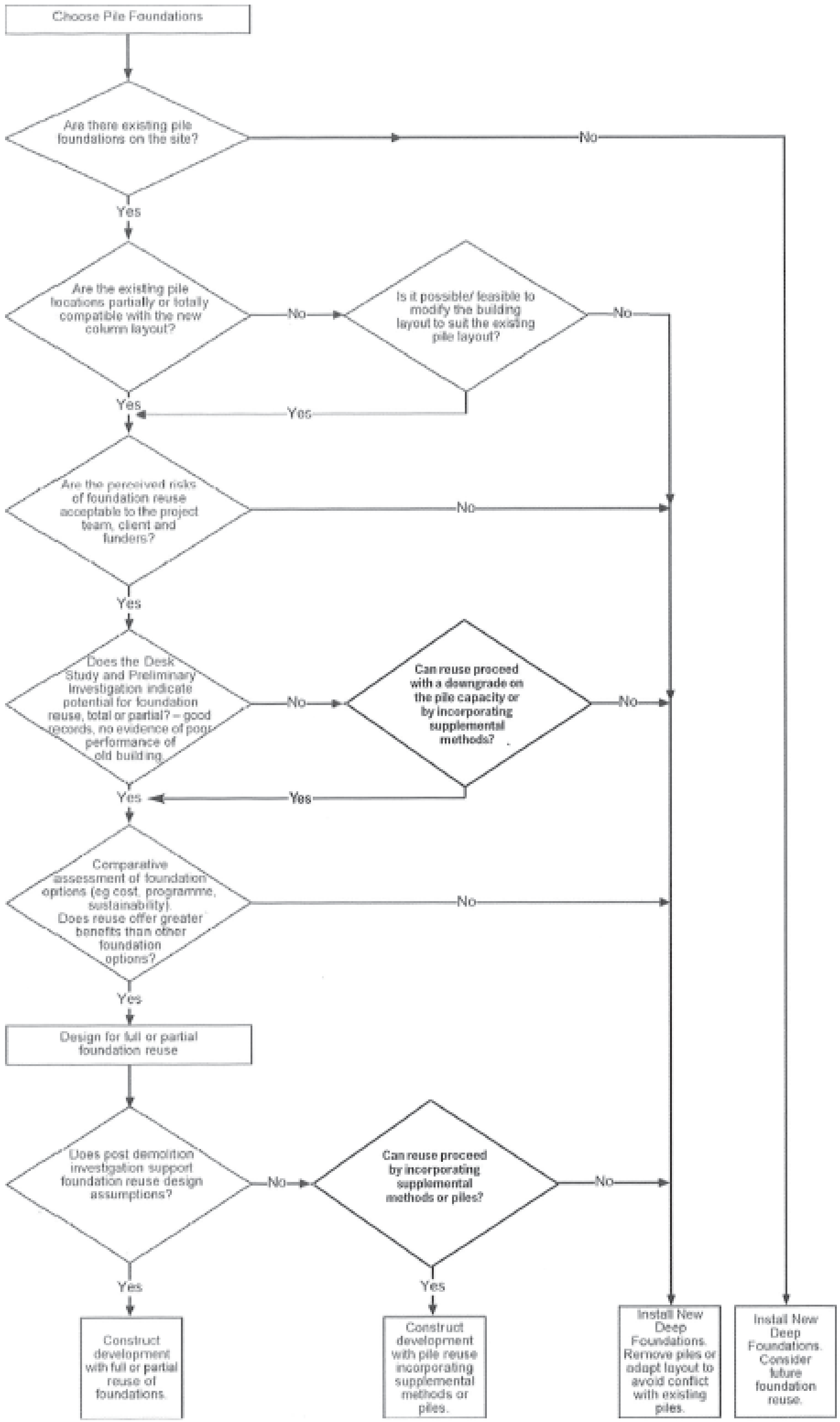

Figure 4-9: Decision method for reuse of deep foundations [74]

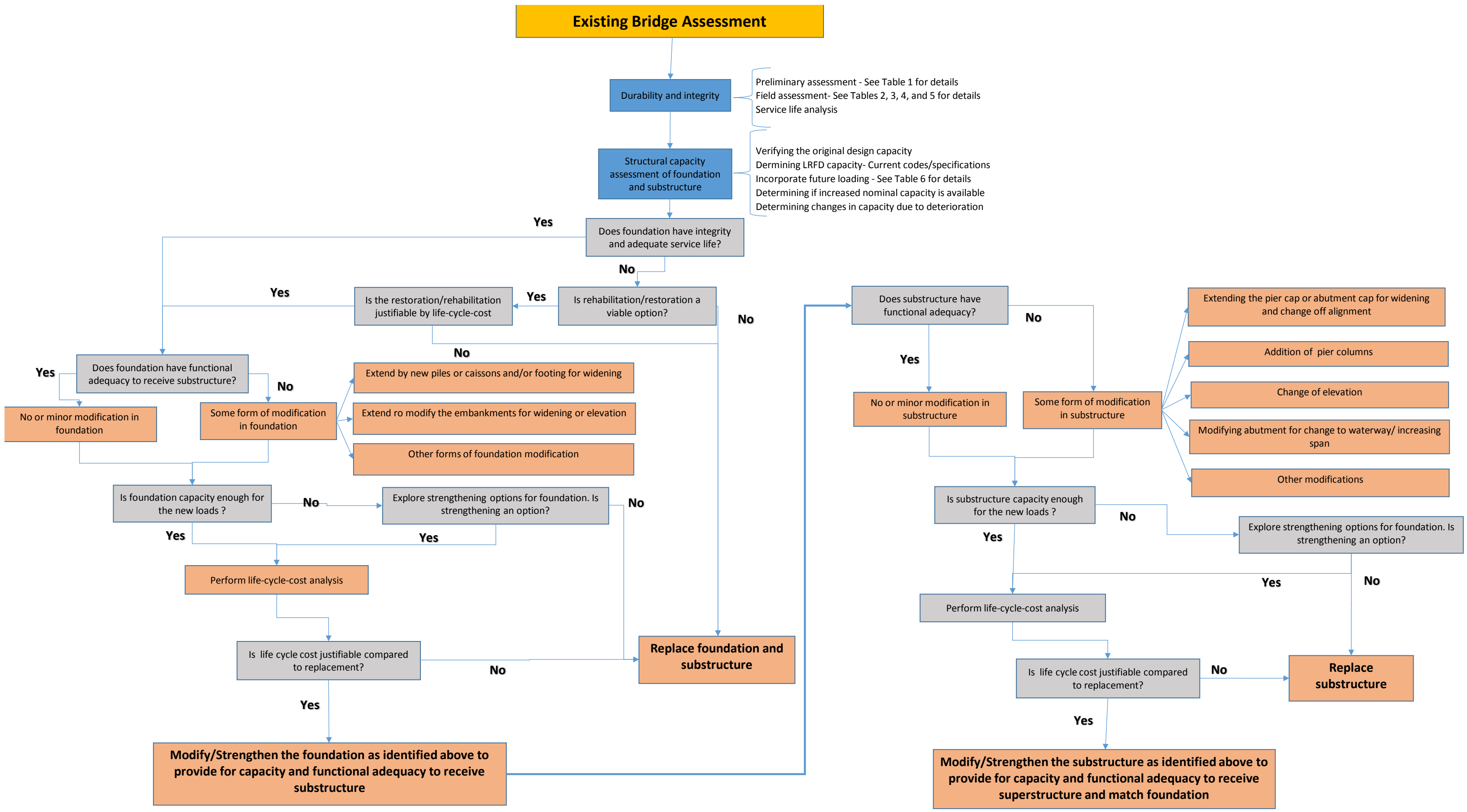

Figure 4-10: reusing of foundation and substructure

4.6.1 Life Cycle Cost Analysis

Maintenance, repair/rehabilitation, and retrofitting/modification costs for bridges or components including the substructure are affected by age and desired remaining service life, the level and suitability of use, and the quality and level of preventive maintenance received as well as the extent of retrofitting and modifications to the existing structure. Other factors such as the ease of maintenance, availability of material and service, and need to limit downtime should also be considered. Accurate analysis requires accurate data. The Life Cycle Cost Analysis (LCCA) of maintenance, repair, and retrofitting applications should be based on the best operating experience and cost data available for the system being evaluated.

A common problem faced in structural maintenance is whether an existing system or component should receive major repairs to extend its useful life, retrofitted, modified, or whether it should be replaced with a new one. The problem may apparently contain more than two alternatives of repair or replacement. On the bridge component level, in addition to the repair and replacement options, several strategies comprised of various levels of repair, retrofitting/modifications and replacement can be studied. This may arise from the fact that not all elements of bridge under consideration are at the same condition or need the same repair/maintenance levels.

In any case, the problem can be evaluated using modified form of the TLCC (Total Life Cycle Cost) method of LCCA for inclusion of various alternatives. If the alternatives have unequal useful lives, the comparison should be made on an annual worth (or equivalent annual cost) basis. While the cost of maintenance may run at higher levels for the repair and maintain option, there is no economic advantage to pursuing replacement unless the annual value or cost is significantly less. Costs included in the analysis should include expenses associated with the acquisition and installation; construction that must be performed to accommodate the new components; maintenance and future upgrades.

If a system or component is performing satisfactorily, routine maintenance should be provided to ensure it continues to perform. On the other hand, the bridge or components may deteriorate unexpectedly due to environmental or other causes to a level that routine maintenance would not be able to assure their service life. In this case, special maintenance or repair activities could become necessary. The additional cost of such special activities may justify consideration of replacement option. When replacement is clearly required, the total life cycle cost method can also be used to select between alternative replacement systems or components. To this, the option of retrofitting or modifications to the structure for conforming to its desired function should be added. The latter may involve a combination of repair/retrofitting and addition and changes to physical and geometric envelop of the structural components. Typically, the choice is between a replacement with a higher initial cost and a lower ongoing maintenance cost or one with a lower initial cost and a higher maintenance cost.

Another maintenance question that might be addressed using LCCA is what level of maintenance should be provided to produce the lowest total life-cycle cost over the service life of the system or component? Different levels of maintenance will increase or decrease the total life cycle cost. The analysis involves determining operating costs and benefits associated with alternative levels of maintenance, calculating the total life cycle cost over the remaining service life, then comparing results and selecting the optimum level of maintenance. Because there is limited funding available for repair and replacement work, it is vital that agencies provide a level of preventive maintenance which will prevent premature failures and allow the most cost-effective use of maintenance funds.

However, it is realized that cost efficiency may not be the only parameter to be considered in a decision-making process. Position and role of a bridge structure in a highway network is one parameter that may significantly affect the decision making. In other words, interruption in the traffic at local and network level and importance of the road in which the bridge is located plays also a significant role. A life cycle cost analysis of a bridge isolated from the system, though effective and useful, would not be able to quantify all the existing factors. The LCCA results should be evaluated in conjunction with global or system strategic considerations. These may include events related to bridge closure and delays that may have consequences above and beyond monetarily measurable costs.

4.6.1.1 Basic steps in LCCA

In general, steps and procedure for an overall LCCA related to bridge structures can be listed as below:

- Characterize bridge, bridge subsystems, and its elements
- Define planning horizon, analysis scenario, and base case
- Define alternative bridge management strategies
- Specify/select appropriate deterioration models and parameters
- Estimate costs
- Calculate net present values
- Run a sensitivity analysis
- Review results (if not acceptable, modify the strategies and repeat calculations)
- Select preferred strategy

4.6.1.2 Bridge and its elements

The life cycle cost analysis in this study focuses on substructure and foundation, assuming that the superstructure has been identified as deficient and requires replacement. The evaluation of durability, integrity, and capacity of the existing substructure should be performed prior to the life-cycle cost analysis to provide the necessary information.

4.6.1.3 Planning horizon, analysis scenario, and base case

Planning horizon is the service life expected from the bridge as a whole from this point on.

A wide variety of factors may influence the analysis scenarios. This include the current state of the bridge substructure and foundation, the importance of the bridge in the transportation network, susceptibility of the existing bridge substructure to damages causes by extraordinary events defining the vulnerability costs are among these parameters. Adverse environmental effects including sea water rise, storms, flood, earthquakes will add to the vulnerability of bridge subsystems.

Existing traffic volume and its trend also influences the results. This will influence the current and future cost of interruption to operation of the bridge.

Calculation of present value for various repair/replacement strategies rely heavily on the discount rate. The discount rate should be determined based on comparable long-term projects, the real discount rate (inflation incorporated) for this analysis.

The base case for life cycle cost analysis is normally defined as "do nothing" option and generally includes only normal maintenance and vulnerability costs. This scenario will only be valid if the substructure and foundation capacity at its current state is acceptable and it provides for the functionality of the bridge without any modifications. However, depending on the results of durability and integrity evaluation, this case, the "do nothing" option may require extensive inspection to assure safety and is expected to impose additional costs due to potential for failures and higher risks for extraordinary events.

4.6.1.4 Alternative bridge management strategies

Based on the current condition evaluated for substructure and foundation, and available methods for repair, retrofit, modifications, or replacement, following strategies, similar variations or combination of individual strategies can be selected for inclusion in the LCCA:

Base case- The case of "do nothing" that may involve some minimal repair and should include some monitoring and inspection regimen prescribed based on the current condition. Ongoing maintenance activities should be considered during service life to prevent significant degradation in the condition. Potential for failure and vulnerability to natural hazard should be evaluated accordingly.

Repair- Apply the necessary repairs to elevate the current state to a desirable level. This option will also require certain monitoring and inspection regimen, as well as maintenance required for upkeep. Potential for failure and vulnerability to natural hazard should be evaluated accordingly.

Repair-Strengthening- This may be a combination of some repair and also strengthening activities. Repairs are assumed to be repeated at certain intervals due to limited durability and potential for new damages. Strengthening shall be designed to address the capacity requirements. Potential for failure and vulnerability need to be evaluated accordingly.

Structural and/or geometric modifications- This may involve major strengthening using additional components and extensions for geometric compatibility. Monitoring and inspection regimen should be prescribed according to the condition of existing components and type of the new additions. Potential for failure and vulnerability needs to be evaluate based on the condition of the existing substructure and expected behavior of the amended subsystem.

Replace- This strategy includes removal of existing substructure/foundation and replacing with new. Accordingly, potential failure and vulnerability reduces or disappears. Routine inspection can be prescribed at long intervals.

The strategies described above need to be customized and modified based on the state of substructure and foundation on case-by-case basis. For example, in some cases, the foundation may be adequate when the substructure requires repair, strengthening, or modification. In other cases, the substructure may be adequate and only foundation requires strengthening and modification.

4.6.1.5 Deterioration models and parameters

In one approach (BLCCA, NCHRP 483, Bridge Life Cycle Cost Analysis), the condition of the elements is characterized in terms of a distinct set of possible “states” and possible transitions from one state to another [75]. Element’s aging can be presented as successive transitions from state to state based on anticipated environmental conditions, repair actions, and other parameters that can in some cases be estimated using models similar to decay, wear, or fatigue functions. The condition (state) of substructure and foundation elements shall be determined through evaluation procedure described earlier. Deterioration models for concrete and steel need to be identified from those available, or develop new models according to the need and conditions observed for the existing substructure and foundation. Procedure or software available for life cycle condition analysis can incorporate such deterioration model to reflect the degradation of structural health in time, transition from one to another state, and recovery of health index resulting from repair activities.

A health index is also introduced that indicates the need for repair/replacement. For example, reducing the health index from its original value of 100 to threshold index of 50, signals the need for replacement.

4.6.1.6 Cost estimates

The costs associated with the various options are divided into three groups; initial, distributed/periodic, and vulnerability costs. The initial costs are related to installation of any monitoring systems, repair, strengthening/modifications, or replacement. Distributed/periodic costs are related to inspection, maintenance of the monitoring system, and future periodic repairs.

Vulnerability costs are related to the potential cost of repair/replacement to the bridge substructure and foundation due to loss of load carrying capacity from ongoing damages such as corrosion-fatigue and extraordinary events (hurricanes, earthquakes, flooding, etc.).

Depending whether the bridge is in the zones that are prone to natural hazards, there could be significant probability for various structural damages, therefore, resulting in significant agency and users’ costs. To associate costs to extraordinary events, return period and damage scenarios need to be considered for each category and bridge vulnerability level.

With the exception of periodic future repairs, the costs in distributed/periodic and vulnerability cost groups are estimated for the time they occur and are divided by the return interval to obtain annual equivalent distributed costs.

Costs in each category have two elements, agency cost and users’ cost. Agency cost refers to the actual cost of implementing an event such as contract cost for repair or inspection. Users’ cost refers to cost born by the users of the bridge, i.e., drivers and cars/trucks, for delays or detours related to activities on the bridge. Cost to businesses around the bridge can also be included.

Costs related to each strategy should be calculated using available data for every category of initial, periodic/distributed, and vulnerability. Some research and deductions may be needed to estimate some of the costs that are not readily available or properly formulated.

4.6.1.7 Present values

Among the costs, the initial costs for various strategies can be assumed to occur at the end of the first year or distributed along the anticipated time required for the actions related to initial cost. Distributed annual costs and vulnerability annual costs can be assumed to start at the end of the first year and span over the analysis horizon. To account for the time value of the costs, present value of all costs related to each strategy is calculated at the beginning of the first year.

Present value calculations and analysis of results can be performed using available software, or simply use computer spreadsheets supplemented by the available formulation [75]. The analysis software, BLCCA, that accompanies the NCHRP Report 483, Bridge Life Cycle Cost Analysis has additional analysis and report capabilities that are very useful for presentation of the results [75]. It accepts information on deterioration models and calculates the health index for various strategies. Present values calculated using any of these tools for various groups of costs can be tabulated and illustrated through charts for clarity. A sample calculation results for a repair/replacement project related to the Luling Bridge in Louisiana, is shown in Figure 4-11 [76, 77]. Although, the repair/replacement considerations in this project was not related to substructure, the LCCA procedure, assumption, deterioration models, cost calculation and other estimations can be used as model for any bridge project where strategies such as repair, replacement, and combination of repair/replacement needs to be considered.

To demonstrate the deterioration trends and the effect of corrective actions, planned or unplanned, BLCCA software can be used to generate the variation of the health index during the planning horizon of the project. Sample results from the sample LCCA [76, 77] is presented here for visualization of analysis and results. For example, for the Base Case, Figure 12, deterioration is expected to be faster and corrective actions at intervals are assumed to represent the unplanned repair and cable replacement dictated by the vulnerability due to corrosion and fatigue process. A health index of near 50 is when the replacements are dictated. Deterioration trend reduces with strategies involving repair and replacement (Figure 4-13), and trend improves significantly with Replace strategies (Figure 4-14).

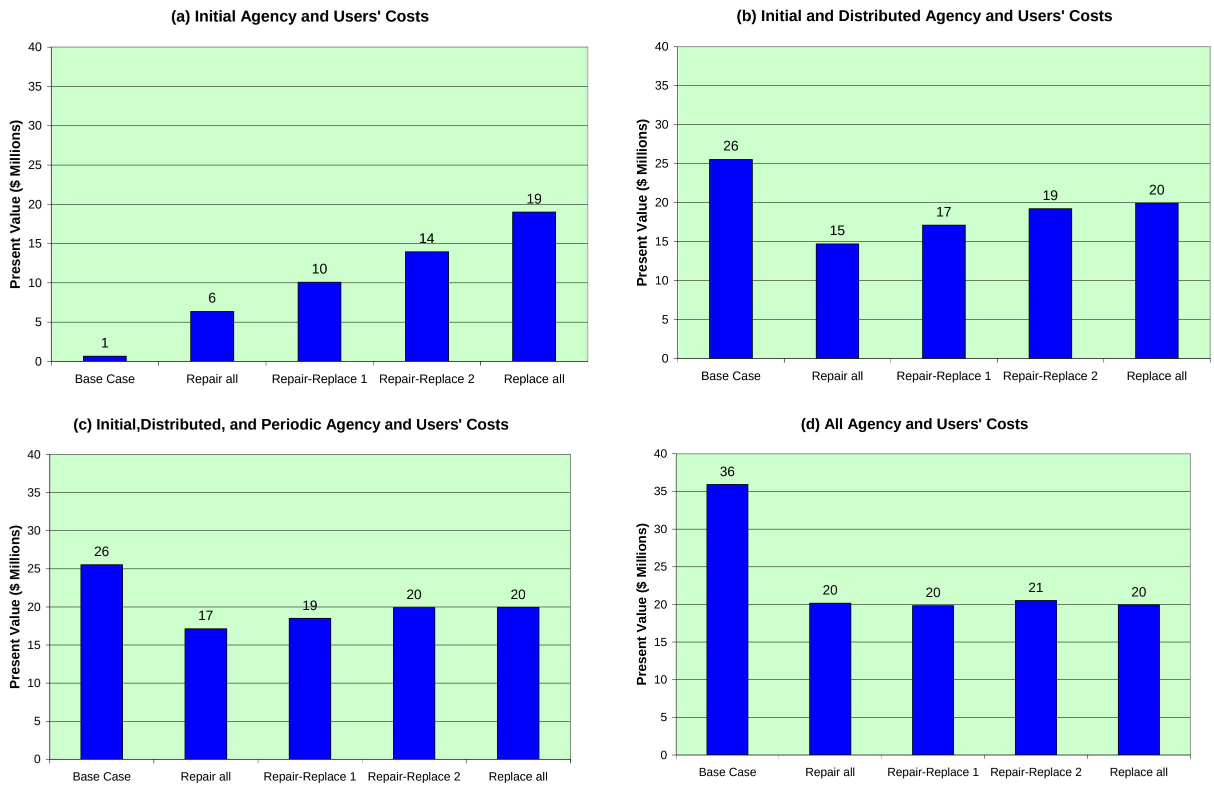

Figure 4-6: Comparison among present value of total costs (agency+users) for various strategies [76, 77]

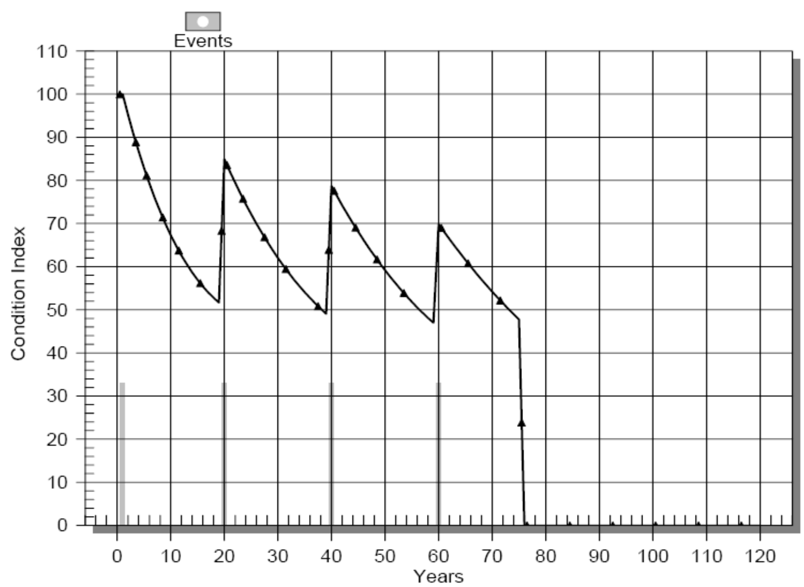

Figure 4-7: Health Index variation for Base Case Strategy

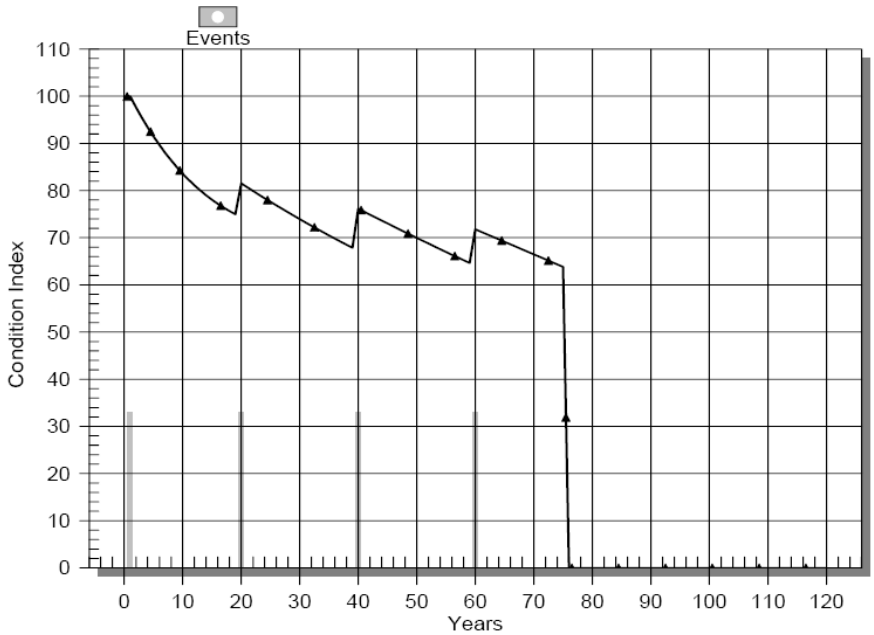

Figure 4-8: Health Index variation for Repair Strategy

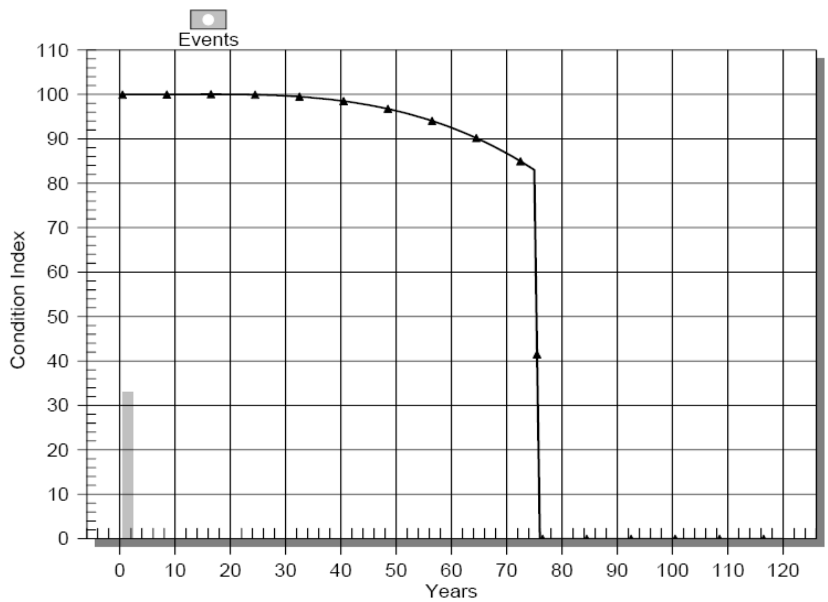

Figure 4-9: Health Index variation for Replace Strategy

4.6.1.8 Sensitivity analysis

The present values of costs estimated for each strategy are sensitive to variation of several parameters. Among those, perhaps the most influential are the discount rate and estimated event costs. The effect of discount rate variation is pronounced for strategies that have higher proportions of distributed, periodic and vulnerability costs. These costs are spread over the planning horizon and therefore have been discounted for present value calculation. If the actual discount rate is lower than that considered in this study, the present value of these costs will be greater than that reported here, and vice versa. To demonstrate this effect, a sensitivity analysis can be performed. Here, sample sensitivity analysis results for the Luling Bridge project using the BLCCA software for variation of discount rate between 2 and 8 percent is presented (the original rate considered for present value estimation was 3.8 percent). Figure 4-15 shows the result of sensitivity analysis for total combined (users+agency) costs. Results show the trend described above. The present value estimated for the Base Case which has the greatest distributed costs is the most sensitive to discount rate variation.

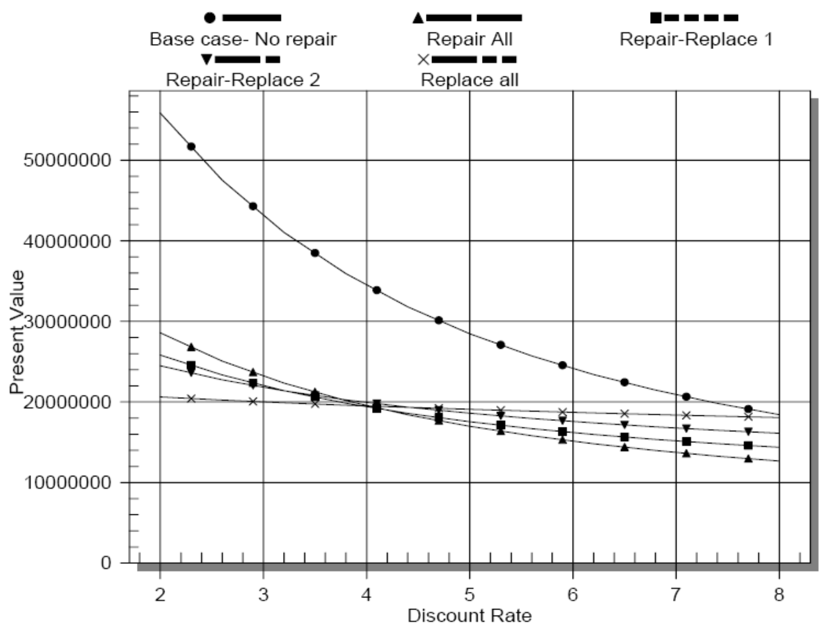

Figure 4-10: Sensitivity of total combined costs to variation of discount rate

The variation of event costs also affects the total combined present values for various strategies. For example, the initial cost variation, cost in year-1, will not affect significantly the Base Case costs because of the very low initial cost associated with that strategy. On the other hand, variation of initial costs will significantly affect the relationship and order of the remaining strategies because the initial cost is a large portion of the total cost for those strategies and total combined costs are in very close range from each other. This effect is more pronounced for the case of variation of initial cost for the Replace strategy that has the highest initial cost. Figure 4-16 shows a sample relationship among total combined costs of various strategies when the initial agency cost of the Replace option varies between minus and plus 20 percent of the cost originally considered for estimations [76, 77]. Similar trends exist when variation of initial costs of other strategies involving repair and replacement is considered.

Variation of distributed and future cost will on the other hand affect more noticeably the strategies that these costs form a major part of the total present value. For example variation of the inspection costs will affect most the Base Case strategy.

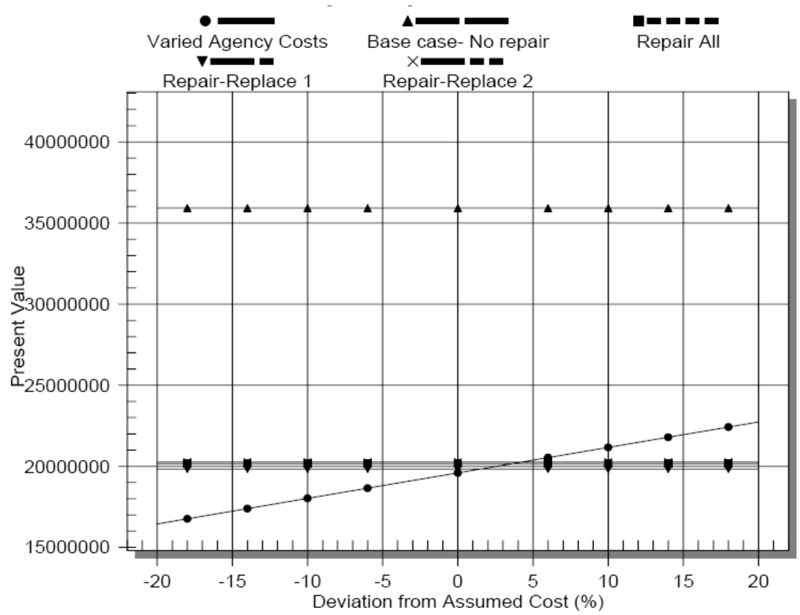

Figure 4-11: The effect of variation of initial agency cost of Replace all strategy

4.6.1.9 Preferred strategy

With the information generated using LCCA, the bridge owner can decide on the strategy fits best the purpose of the project. In addition to the factors considered in LCCA analysis, the bridge owner may want to consider other socio-economic or political parameters in their decision. The logistical importance of the bridge also may present as a strong factor. For example, bridge in the hurricane (or other natural or manmade hazard) evacuation routes may warrant speedy strategies even though they offer costlier option.

4.6.2 Social Impacts

Accelerated bridge construction technology can decrease the construction time for bridge replacement projects. The impact of decreasing construction time and limiting onsite work zone activities can ultimately decrease delay in traveling, vehicle operation costs, and risks associated with delays and construction zone safety. This can help to prevent further depletion of natural resources and help toward providing for a sustainable environment. These factors have been recognized by FHWA in relation with highways and roadways construction societal impacts [78].

The main social impact of highway and bridge construction is increasing the safety in work zone and nearby areas. The adverse effect of prolonged construction can decrease travel speed, reduce traffic mobility, increase probability of accidents, and cause detours, that in turn would result in extending the traffic interruptions to a larger zone within the network. These holistic impacts of work zone can be considered as social cost of construction and should be taken into account when selecting the construction method and type of elements and subsystems for substructure and foundation [79]. Considering monetary value for the time of travelers, vehicle depreciation, increasing carbon footprint, cost to businesses affected by traffic interruptions, etc., in the life cycle cost analysis as users' cost can incorporate most if not all societal impact in the decision making process.

4.7 Methods of Retrofitting/ Strengthening

Durability, integrity, and capacity evaluation may determine deficiencies in the existing bridge. To address the deficiencies and improve bridge capacity, strengthening and retrofitting of foundation and substructure can be designed and implemented. It should be considered that strengthening or retrofitting to address one issue may impact other aspects of the construction. Additionally, minor or major modifications may need to be applied to the existing foundation and substructure to provide suitability to superstructure regarding alignment, widening, and elevation.

Some of the strengthening, retrofitting, and modification options for substructure and above ground elements identified by the NCHRP Synthesis 505 includes increasing capacity using pier stem widening, adding tiebacks, decrease loading on abutment with replacement of lightweight backfill, improve soil stability using soil nail, and wall encasement of piers bent [57].

Addition of deep foundation or micro piles to increase capacity of foundation, and implementation of global and local ground improving techniques including grouting on the tip of foundation can increase foundation capacity.

4.7.1 Substructure

The strengthening and retrofitting methods for concrete elements as per FHWA Report [58] are summarized in Table 4-11. As shown in this table, different methods can be used to protect the elements from carbonation, chloride, and other harmful chemical substances. Each method extend element life in a different way. As described in this table, cover enhancement can also be used to enhance the strength of the elements.

Table 4-11: Strengthening of concrete elements [58]

Strengthening methods	Comment
Patching	Patching with Portland cement concrete (PCC) can increase service life from 5 to 10 years Shotcrete can Increase service life from 10 to 15 years The service life can be increased
Cover enhancement	Concrete impacted by carbonation or chloride Removal of concrete affected by carbonation and chloride and replacing with high quality concrete with proper air entrainment
Fiber-Reinforced Polymer (FRP) wrapping	Prevents further intrusion of hazardous substances to the element, and provides higher strength
Reinforcing with new concrete face	Removing of segments exposed to carbonate or chloride and replacing with new ones Place a new concrete face without removing the existing element
Doweling	Add additional rebar into the existing element with drilling, inserting rebar, and grouting
Cathodic Protection	Prevent corrosion by enforcing the rebar to be in cathode state Impressed current system method provides continuous current to charge differential between rebar and Anode Galvanic system connects sacrificial anodes to rebar to protect them
Electrochemical chloride extraction (ECE) and re-alkalization (ECR)	Use impressed current to force out the chloride Life extension between 5 and 10 years Exposure to carbonate is not addressed in this method

The main problem for steel elements is corrosion. The sections that has corrosion should be repaired. Repair options for underwater sections are summarized in Table 4-12. The description of repair techniques for steel elements are listed in Table 4-13. As shown in Table 4-13, different methods can be used to prevent further corrosion. Wrapping or jacking can also be used to increase the strength of steel elements [58].

Table 4-12; Repair options for underwater steel elements [65]

Damage	**Repair Option**
No Visible Deterioration	Coatings, Pile Wrap
<15% section loss	Pile Jacket
15%-30% section loss	Pile Jacket with Reinforcement
>30% section loss	Partial Replacement

Table 4-13: Strengthening techniques for steel elements

Strengthening methods	Comment
Encasement, jacketing, and wrapping	Steel member can be encased in concrete or wrapped in waterproof membrane Prevent further corrosion Can provide additional strength for element
Paint and coating	Usually used when the element is in good condition and original coat is not as effective as it should be
Cathodic protection	For underground or underwater elements Impressed current or galvanic system can be used

Furthermore, it should be noted that the existing foundation and substructure designed based on the older design code may require new considerations per the updated design code such as seismic and other hazard considerations [58]. Therefore, the existing foundation or substructure may face higher load demands for which they are not designed for. For example, the columns may not have enough confinement and shear strength to resist extreme hazard events. The following table lists the retrofitting options to improve and increase the capacity of existing elements.

Table 4-14: Retrofitting of existing elements [58]

Retrofitting method	Comment
Strengthening	Increase elastic and ultimate strength of elements depending on the extreme event loads
Improvement in displacement capacity	Increase inelastic behavior of element to improve displacement capacity of the element
Force limitation	Define deliberate yield points to prevent member overloading
Response modification	Change in members load transmission by providing additional stiffness to selected members
Site remediation by ground improvement	Limit liquefaction potential, site amplification, or other hazards using ground improvement techniques
Acceptance of damage to some elements	Allow damage to some specific elements during hazard to prevent structural instability of the bridge
Partial replacement	Replace elements that cannot resist extreme hazards

4.7.2 Foundation

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4.8 Extension or Amending to the Exiting Substructure and/or Foundation

Usually, the use of additional elements and modification in the existing foundation and substructure is needed to prepare required functional adequacy and suitability to the superstructure, or to increase the capacity to address changes in the loading.

Possible options for modification and extension of substructure and foundations are described in the next sections. Based on the selected options and modification in the substructure and foundation, an analysis should be conducted to account for changes in loading and bridge elements. In performing these analyses, the effect of superstructure removal, construction sequence, and changes to the existing elements should be considered. When the existing bridge superstructure is removed, the loading on the existing substructure and foundation will reduce or change. Accordingly, the deformation and settlement occurred in the existing substructure and foundation will not be completely recovered. This will make the existing substructure and foundation elements stiffer than the new added elements constructed on new foundation, therefore causing uneven distribution of loads between elements that needs to be considered in the analysis.

4.8.1 Substructure

The extension and modification options for the bridge substructure and foundation are:

- Adding new line of column, pier, and wall between existing lines of substructures.
- Extending pier cap and abutment cap to accommodate the wider superstructure or new alignment
- Pouring additional concrete adjacent to pier or extending the pier wall
- Extending the footings to accommodate the new substructure elements
- Addition to foundation (deep or shallow) to accommodate larger/modified footing
- New pier construction to accommodate new superstructure and new configuration.

Extension, modification, and strengthening of bridge substructure is conducted to increase capacity of substructure and/or to provide for its functional adequacy according to the predicted future demand. One method of increasing functional adequacy is widening of existing bridges. In this case, new substructure elements are needed to provide required capacity and new geometry. This may require increasing the size of piers and pier caps (both by length and width) to accommodate the new superstructure. Consequently, the footing size for the existing bridge may need be extended as well.

4.8.2 Foundations

OU TO PROVIDE THEIR WORK FOR THIS SECTION

5 Survey

To investigate and identify the current issues and procedures in the selection, construction, and design of ABC bridge foundation and substructure, an online survey was distributed among the stakeholders. The stakeholders included, but not limited to state DOTs through AASHTO Committee on Bridge and Structures. To distribute and perform analysis on the survey results, the online Qualtrics instrument was used. The survey had 3 following sections (Figure 5-1). Appendix A also provides survey questionnaire.

Section 1: Administrative questionnaire

Section 2: Type of bridge construction questionnaire

Section 3: New bridge construction questionnaire

Section 4: Existing bridge construction questionnaire

In section 1, general questions were asked about the agency and the position of the person who filled the survey. This information was saved to contact the participant in case of requiring further details.

After filling the first sections, the participants were directed to Section 2. In this section, participants were asked if their agency had experience in implementing ABC technique in the construction of bridges. They were also asked if they used the ABC technique in the construction of new bridges or/and existing bridges.

Section 3 questions were asked of participants who had experience in implementing ABC technique in the construction of new bridges. Some detail of agency experience in implementing ABC technique in the construction of new bridges, strategies in selecting the bridge components, and issues in the design and construction of bridges were asked.

Finally, if the participant had experience in implementation of the ABC technique in relation with existing bridges, section 4 questions were asked. Questions dealt with the agency's experience in the use of the ABC technique in the replacement, reuse, retrofitting or extension of existing bridges. In this section, questions about the method they used to select the bridge components, the decision-making procedure in replacement or reuse of bridges were included.

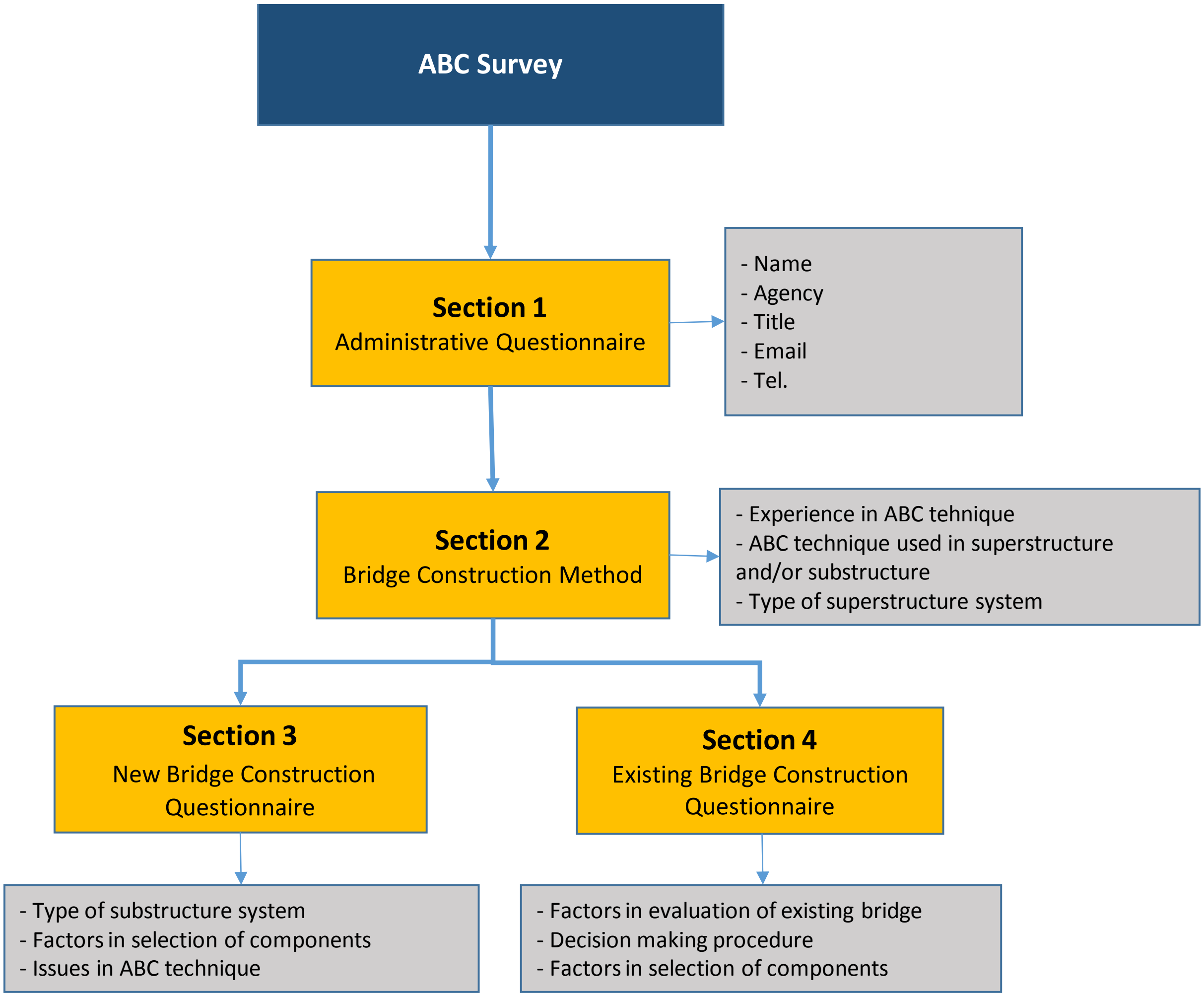

Figure 5-1: Survey sections

5.1 Survey Participants

20 agencies participated in filling the survey questionnaire (Figure 5-2). All of them were state Department of transportations. The list of participants is summarized in Table 5-1. These departments were located in different part of the United States. Figure 5-2 shows the distribution of agencies in the United States.

Table 5-1: Survey participants

Item	Agency	Title
1	Rhode Island Department of Transportation	Managing Engineer
2	Oklahoma DOT	Director of Bridge Design
3	Indiana Department of Transportation	Structures Program Manager
4	Vermont Agency of Transportation	Asst. State Structures Engineer

5	New Hampshire Department of Transportation	Administrator Bridge Design
6	Missouri Department of Transportation	State Bridge Engineer
7	Ohio Department of Transportation	Administrator
8	Florida Department of Transportation	Assistant State Structures Design Engineer
9	North Dakota Department of Transportation	Engineer
10	Montana Department of Transportation	Bridge Design Engineer
11	Nebraska Department of Transportation	Assistant State Bridge Engineer
12	Michigan Department of Transportation	Chief Bridge Engineer
13	Iowa Department of Transportation	Chief Structural Engineer
14	North Dakota Department of Transportation	Assistant Bridge Engineer
15	Wisconsin Department of Transportation	Structures Development Supervisor
16	Kansas Department of Transportation	Design Leader
17	Michigan Department of Transportation	Foundation Analysis Engineer
18	Washington State Department of Transportation	State Bridge Design Engineer
19	State of Alaska Department of Transportation	Technical Engineer II
20	Texas Department of Transportation	State Bridge Engineer

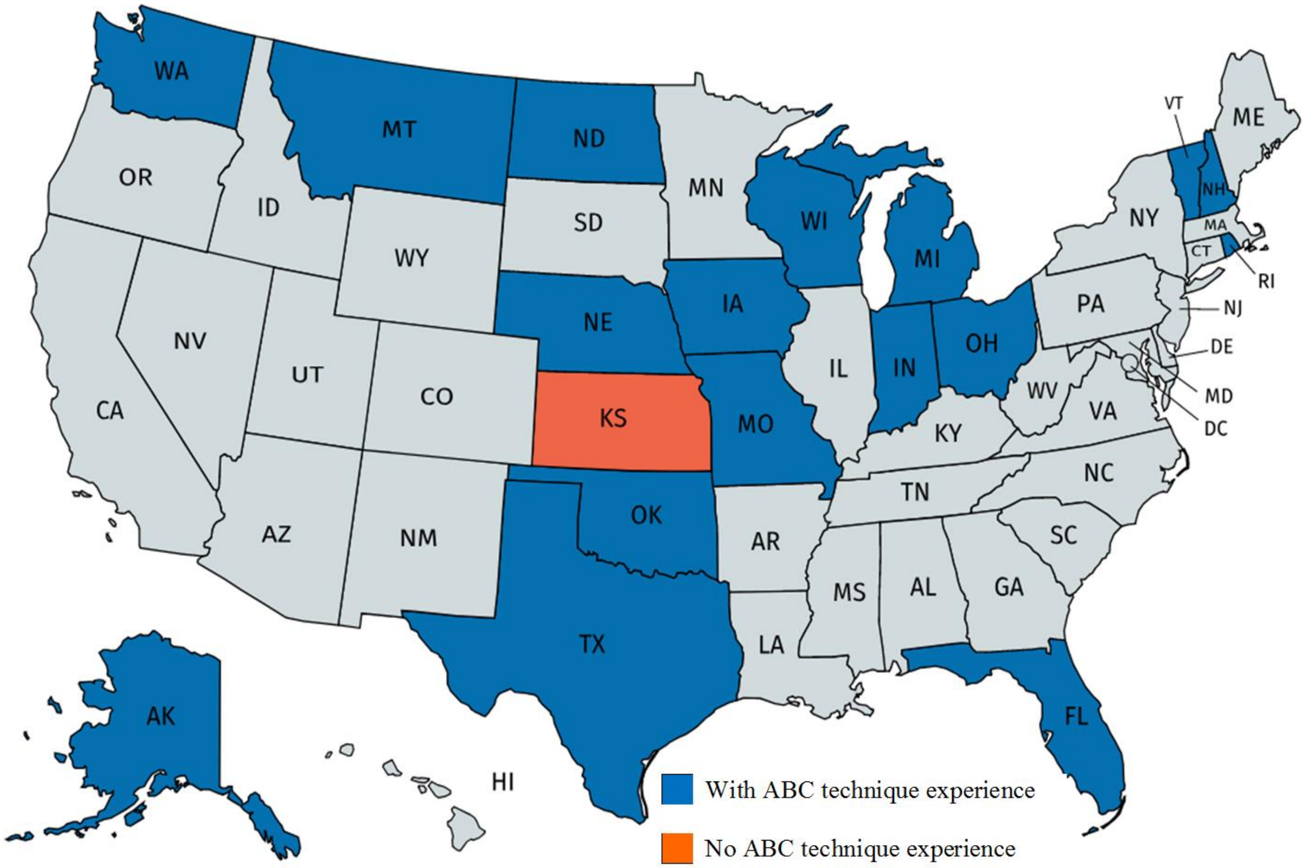

Figure 5-2: Distribution of participants in the survey

5.2 Survey Results

Ninety percent of the survey participants who had experience in the application of ABC technique, had their experience in the construction of bridge superstructure, substructure, or foundation (Figure 5-3). 10% of respondents implemented the ABC technique only in construction of bridge superstructure.

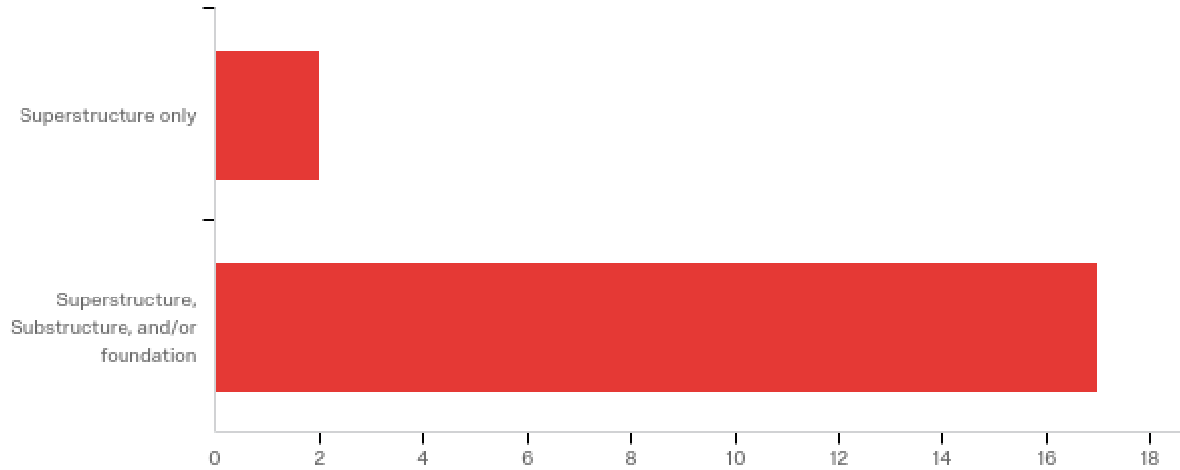

Figure 5-3: Application of ABC technique in bridge construction

The results also showed that 75% of participants had experience in implementing the ABC technique in constructing new bridges, where, 25% of participants had experience in applying the ABC technique in replacement or retrofitting, of existing bridges with an option to reuse, extend, or modify the substructure/foundation (Figure 5-4). Michigan State DOT was the only state had experience in implementing ABC technique in construction of both new and existing bridges.

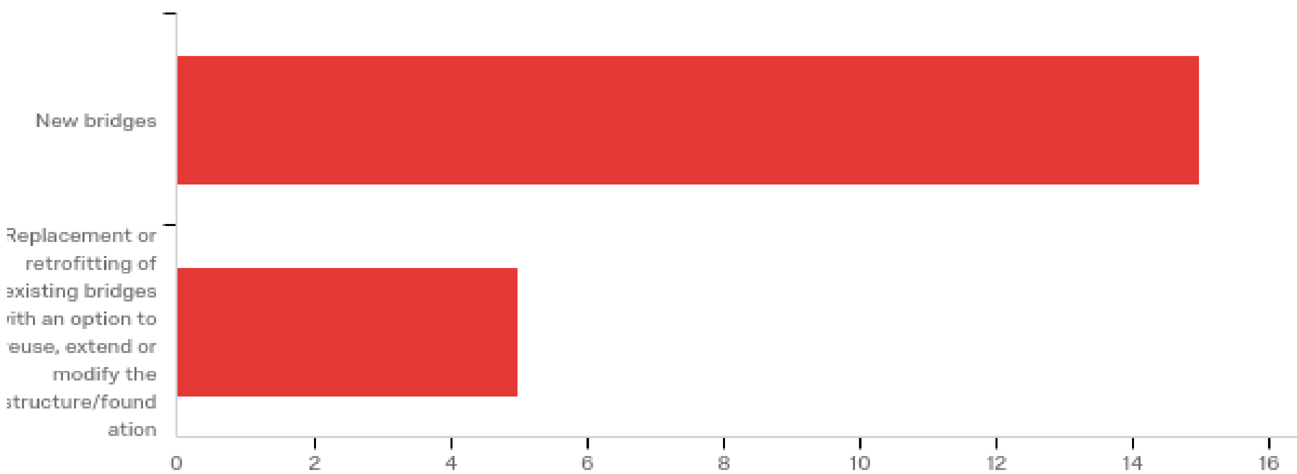

Figure 5-4: Implementation of ABC in the construction of new bridges or existing bridges

5.2.1 ABC Construction Method

SPMT and lateral sliding, along with the use of crane for prefabricated elements have been identified by the participants as construction methods used in their projects.

5.2.2 Superstructure elements

Prefabricated superstructure elements were used commonly. The most common elements used in the ABC projects are listed below.

- Partial and full precast deck,

- Butted box beams,
- Precast and prestressed beams with topping slab and modified shear key,
- Side-by-side box beams or cored slab superstructures,
- Spliced curved, U-beams,
- Voided slab superstructures

5.2.3 What is needed to prepare agencies to adopt the ABC Technique?

In this section, participants were asked to describe what the agency needed to better implement ABC. Their response is summarized below:

1. Training of contractors, agencies and DOT staff about ABC. There is a lack of knowledge about how, where and why ABC technology can be implemented.
2. Designers need to be educated about the type of elements, connections and shapes they can fabricate to support ABC type construction.
3. Having a guideline for designers and agencies that help them to select the best method in the construction of a bridge based of construction duration, construction cost, and the reason for choosing a specific method can help to facilitate the use of ABC technology.
4. Case study details are required to quantify the road user cost and ABC benefits to give ideas on how to implement ABC. This can also can address the unfamiliarity of owners and agencies to address this issue.

5.2.4 Substructure elements

The common substructure elements used by the participants included:

- Precast caps on precast piles supporting precast superstructure elements (side-by-side box beams/or cored/hollow slabs)
- Precast concrete pier cap
- Precast concrete columns
- Precast concrete backwalls
- Precast concrete approach slabs
- Approach slabs with integrated concrete rail, concrete-filled steel pipe, and
- Pile extension bents that can be constructed without a cofferdam and the pipe pile serves as a permanent

5.2.5 Foundation Elements

The most common foundation elements indicated by the participants are:

- Steel piles,
- Spread footings,
- Drilled shafts,
- Precast grade beams
- Precast abutment
- Pile caps

5.2.6 Factors in Selection of Substructure and Foundation Systems

The most important factors affecting the selection of substructure and foundation bridge systems and components are:

- Cost and speed,
- Bridge span
- Soil condition and location of rock under the surface of ground
- Stream crossing
- Critical path of bridge that determines amount of precast substructure need
- Equipment
- Traffic restrictions
- Precast elements transfer issues
- Risk mitigation
- Contractor familiarity
- Constructability
- Design compatibility
- Seismic performance
- Long-term durability
- Quality and safety of work

5.2.7 Guideline for selection of bridge components

Participants did not mention a particular written guideline for selection of parts for ABC projects. However, Florida DOT stated that it is often useful to know the traffic restrictions and consider what operations are restricted to night-work and what operations can be constructed during day-time that usually gives the best clues of where to target the precast elements, specialized equipment, etc. Alaska DOT also stated that Alaska Bridges and Structures Manual addresses the design of concrete-filled steel pipe pile bents including the cold climate effects. They added that updates are forthcoming that provide additional design guidance on this type of substructure.

5.2.8 Interaction Between Superstructure, Substructure, and Foundation in the Selection of Components

The following restrictions were reported by the participants.

In some cases, the superstructure type may lend itself to working well with certain substructure types. For example, prestressed tri-deck beams can be cast with integral backwalls. Or, the foundation type will drive whether the abutments are semi-integral or integral. It was reported that the use of semi-integral abutment complicated the details since it was required to pour the abutment diagrams in place. The precast backwall was used to connect the abutment to the end of floor and the approach slab.

5.2.9 ABC technology in bridge foundation construction

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5.2.10 Seismic Considerations in Design of Foundation and Substructure

Most agencies reported that seismic issues were not their concern because they are not located in seismic potential regions. However, seismic considerations were considered for substructures and connections in states that are located in seismic region. Montana DOT stated Seismic effects were considered for the substructures and connections, but most of our ABC structures are relatively small, single span bridges. As a result, the seismic considerations are typically not significant.

Washington State DOT used integral connections at intermediate piers for seismic applications. Also, Alaska reported that pushover analyses of the pier were conducted according to the AASTO LRFD and Alaska DOT manual to consider seismic effects.

5.2.11 Issues in Using ABC Technology

The reported issues and concerns from agencies are summarized here.

Ohio DOT stated they need to make sure that the details allow the roadway drainage to get where it is supposed to go. If a closed drainage system is required, details have to be consistent with obtaining the drainage to the catch basin. Example - precast concrete elements have joints between the elements. If these joints open up, will the roadway drainage go to places not intended. This applies to the bridge and immediately off the bridge. Too many times, roadway drainage is an afterthought. Where the roadway drainage does not function as designed and the drainage ends up in a place not intended, there will be deteriorated components. Also, Montana DOT stated seal the joints between precast elements such as backwalls to prevent water or soil intrusion is in concern. PBES connections and demonstrations through full-scale mock-ups was another reported concern.

TX DOT stated that "incorporates provisions meant to minimize the need for maintenance into our prefabricated elements. In particular, TxDOT relies heavily on the use of High-Performance Concrete in precast elements. Although there are several options for achieving the HPC requirements, in almost all cases that are accomplished by replacing some portion of the Portland cement with Class F fly ash."

5.2.12 Decision making procedure in selecting, replacement, reuse,

Participants reported that there was no procedure to decide whether to replace or reuse the existing substructure/foundation. There were some rare and specific exceptions. For example, it was stated by Rhode Island that retrofit of or replacing a column is an option if there is 60% spalled, cracked or hollow areas. It was reported that bridges are evaluated on a case-by-case basis.

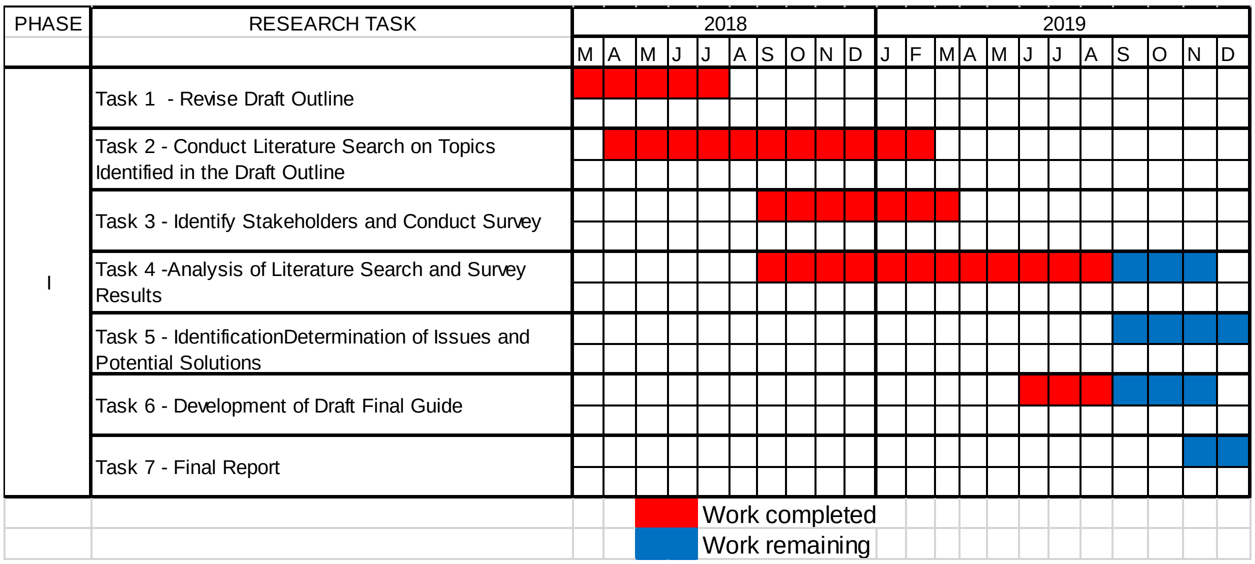
5.2.13 Retrofitting/strengthening

Few responses to this question indicated that for majority, each bridge is considered and evaluated separately. TxDOT frequently extends existing caps on bridge widening projects.

6 Schedule

The bar-chart below shows the schedule and work progress.

Item	% Completed
Percentage of Completion of this project to Date	80



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APENDIX A

Survey Questionnaire

DEVELOPMENT OF GUIDELINES FOR SELECTION OF SUBSTRUCTURE AND FOUNDATION FOR ABC PROJECTS

Section 1

Administrative Information

- ☐ Name (4) ____
- ☐ Agency (5) ____
- ☐ Title (6) ____
- ☐ Email (9) ____
- ☐ Tel. (10) ____
- ☐ Address (7) ____

End of Block: DEVELOPMENT OF GUIDELINES FOR SELECTION OF SUBSTRUCTURE AND FOUNDATION FOR ABC P

Section 2

Start of Block: Type of construction

Q2.1 Has your agency had any experience in application of ABC technique in the construction of a bridge?

○ Yes (5)

○ No (6)

Q2.2 For which of the bridge components the ABC method has been used?

○ Superstructure only (1)

○ Superstructure, Substructure, or foundation (2)

Q2.3 What type of superstructure system and elements and construction method have you used?

____

Q2.4 What is necessary, in your opinion, for preparing your or other agencies to adopt and fully utilize ABC?

____

Q2.5 which of the following options your experience is related to? (please select all that applies). Subsequent questions will be based on the options you select here.

▢ New bridges (1)

▢ Replacement, reuse, retrofitting, or extension of existing bridges (2)

End of Block: Type of construction

Section 3

Start of Block: New Bridges

Q3.2 Please describe/identify the specific system(s) or elements you have used for substructure and foundation.

____

Q3.3 Please provide input for the following questions;

☐ a) What factors have you considered in selection of substructure and foundation systems and elements? (1) ____

☐ b) What guideline or procedure, if any, have you used to select the substructure and foundation systems and elements? please upload any applicable file at the end of the survey (e.g. written guideline, procedure, etc.). (2)
____

☐ c) Has there been any interrelation between superstructure, substructure, and foundation that effected or limited your selection of the type of bridge elements? please explain. (4)
____

Q3.4 Please describe if you have used any type of ABC technology in the construction of the bridge foundation (eg. continuous flight auger piles, Micro-piling, Screw piling, Geosynthetic reinforcement soil-integrated bridge system, etc.).

____

Q3.5 What type of superstructure system and elements and construction method have you used?

____

Q3.6 Did you consider the seismic effect for designing prefabricated substructure and foundation elements and connections? Please specify.

____

Q3.7 Do you know of any maintenance problems or other issues that impact the life-cycle performance of the prefabricated substructure and foundation elements or ABC technology? Please specify.

____

Q3.8

What is necessary, in your opinion, for preparing your or other agencies to adopt and fully utilize ABC?

____

Q3.9 If you have a supporting file, please upload it.

End of Block: New Bridges

Section 4

Start of Block: Existing Bridge Replacement

Q4.2

a) For evaluation of existing substructure and foundation for potential reuse, retrofitting, modification, or replacement, what factors do you consider?

b) Do you follow an established procedure to decide whether to replace or reuse the existing substructure/foundation? Please explain methods used for the evaluation of capacity and service life of existing substructure/foundation.

please upload any applicable file at the end of the survey (e.g. written guideline, procedure, etc.).

____

Q4.3 If you used retrofitting, modification, or extension of existing substructure/foundation, please explain the used methods.

____

Q4.4 If substructure/foundation reuse/replacement was not an option,

- ▢ a) What factors do you consider to select the substructure and foundation elements and systems? (3) ____

- ▢ b) Please describe/identify the specific systems or elements you have used for substructure and foundation system(s). (4) ____

- ▢ c) Did any interrelation between superstructure, substructure, and foundation affect or limit your selection of the type of bridge elements? please explain. (5) ____

Q4.5 What type of superstructure system and elements and construction method have you used?

____

Q4.6 Did you consider the seismic effect for designing prefabricated substructure and foundation elements and connections? please specify.

____

Q4.7 Do you know of any maintenance problems or other issues that impact the life-cycle performance of the prefabricated substructure and foundation elements or ABC technology? please specify.

____

Q4.8 What is necessary, in your opinion, for preparing your or other agencies to adopt and fully utilize ABC?

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Q4.9 If you have a supporting file, please upload it.

End of Block: Existing Bridge Replacement