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Research on Evaluation and Standardization of Accelerated Bridge Construction Techniques

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Research

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16. Abstract

The Michigan Department of Transportation (MDOT) uses Accelerated bridge construction (ABC) to reduce delays and minimize construction impacts. MDOT contracted and completed several bridges using prefabricated bridge elements and systems (PBES). In 2014, two slide-in bridge construction (SIBC) projects were contracted and completed. These two projects included three bridge replacements. Currently, self-propelled modular transporter (SPMT) moves are being planned for three bridge replacement projects. This study goals are to advance the implementations by expanding scoping guidelines to include all ABC alternatives, standardize the bridge slides operations, and develop guidelines for foundation construction while an existing bridge is in service. The tasks completed during this project include (a) reviewing the ABC activities nationally and monitor ongoing ABC projects in Michigan, (b) defining scoping parameters for the implementation of SIBC and SPMT moves, (c) reviewing and evaluating substructure construction and upgrades, along with constructability of deep foundations while an existing bridge is in service, (d) developing specific cost methodologies for SIBC, SPMT moves, and foundation construction, and (e) developing recommendations for updating the multi-criteria decision-making process and the associated software platform by incorporating the updated framework and the cost-benefit analysis models, foundation construction while an existing bridge is in service, and improving SIBC implementations.

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Research on Evaluation and Standardization of Accelerated Bridge Construction Techniques

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EXECUTIVE SUMMARY

INTRODUCTION

Michigan has eleven corridors of National and International significance. The decision principles to guide the management, operation, and investments on these corridors include strategies to reduce delays and minimize construction impacts. Accelerated bridge construction (ABC) is one such strategy employed by the Michigan Department of Transportation (MDOT). The first ABC implementation in 2008 was a fully prefabricated full-depth deck panel bridge system, the Parkview Avenue Bridge. Several prefabricated bridge elements and systems (PBES) were implemented since then. In 2014, three slide-in bridge construction (SIBC) projects were contracted and completed. Currently, self-propelled modular transporter (SPMT) moves are being planned for three bridge replacement projects.

The goal of this project is to promote the following principles:

- Advance the implementations by expanding scoping guidelines to include all ABC alternatives.
- Standardize all bridge slide operations.
- Develop guidelines for foundation construction while an existing bridge is in service.

The specific tasks are as follows:

a) Reviewing completed ABC projects nationally and monitoring ongoing ABC projects in Michigan
b) Specifying additional scoping parameters for SIBC and SPMT moves
c) Reviewing and evaluating substructure construction, upgrades, and constructability of deep foundations while an existing bridge is in service
d) Developing cost/benefit analysis methodologies for SIBC, SPMT moves, and foundation construction
e) Developing recommendations towards standardizing SIBC projects.

STATE-OF-THE-ART AND STATE-OF-THE-PRACTICE LITERATURE REVIEW

The Federal Highway Administration (FHWA) developed a web-based repository for ABC projects in the US. This repository consists of folders for states that have implemented ABC projects. Each project folder consists of sub-folders that may include contract plans, specifications, bid tabs, and other related information such as photos and videos. The information and data on ABC projects outside the FHWA repository are collected by contacting respective Departments of Transportation (DOTs). As of April 2015, a total of 123 ABC projects were compiled including 76 PBES, 30 SIBC, and 11 SPMT moves. This database provides the source of information related to ABC projects.

SCOPING FRAMEWORK FOR CC, PBES, SPMT MOVE, AND SIBC ALTERNATIVES

A multi-criteria decision-making process and the associated software platform was developed during an earlier project. The platform, called the Michigan Accelerated Bridge Construction Decision (Mi-ABCD) tool, formalizes the choices between ABC and conventional construction (CC) alternatives for a specific site. CC is defined as the project delivery alternative not classified as ABC. The framework of Mi-ABCD is expanded to incorporate SIBC and SPMT move parameters. The SIBC and SPMT move parameters are quantitative and qualitative in nature. The quantitative parameters influence the decision-making process based on project specific data. The project specific data in the current decision-making process is expanded to include the parameters specific to SIBC and SPMT move alternatives. The project specific data is defined in three groups: (1) site-specific, (2) traffic, and (3) cost. ABC specific costs are calculated by analysis of data obtained from 123 ABC projects. The cost data can be updated as future implementations are completed.

The qualitative parameters are incorporated in the decision-making process based on user (project team member) preferences, described as 'preference ratings'. The preference ratings are entered by users on a nine point ordinal scale. Ordinal Scale Ratings (OSRs) are implemented to enable alternative analysis with the Analytical Hierarchy Process (AHP). The OSRs are also defined on a scale of 1 to 9 and eliminate the need for pair-wise comparison of parameters and project alternatives, required in the AHP methodology.

FOUNDATION DESIGN, CONSTRUCTION, AND UPGRADE METHODOLOGIES WHILE A BRIDGE IS IN SERVICE

The review included (a) typical foundation types, advantages and limitations with respect to their implementation in ABC projects, (b) foundations implemented in completed ABC projects, (c) a summary of the foundation policies of highway agencies, and (d) a summary of foundations in projects other than ABC, as well as implementation successes and difficulties.

Some factors need to be considered when specifying a foundation type for a particular site. These factors include soil condition, the impact of pile installation on the in-service bridge stability, ground improvement procedures, space considerations for equipment deployment and operation, risks associated with construction of specific foundation types, and associated risk mitigation strategies. Considering these factors, especially the degree of disturbance to the surrounding soil during foundation installation, a foundation type classification is developed. A scoping flowchart is presented for foundation reuse, retrofit, or replacement decisions. Also included are conceptual examples of foundation reuse, retrofit, and replacement.

COST AND BENEFIT ANALYSIS OF ABC

The cost of an ABC project is usually higher and ranges between 6% and 21% over the cost estimate of traditional construction. Complexity, risk, and time constraints are the three main factors that contribute to increased cost. Even though ABC costs more, there are several benefits to the agency and users. Traditionally, for a cost-benefit analysis of ABC, the benefit parameters are limited to detour length and duration of travel on the detour. The user costs are calculated and compared to the costs specific to the ABC alternative. The savings in user cost from reduced mobility impact time are a benefit of ABC. In this project, ABC related costs are calculated from the analysis of data extracted from 123 ABC projects; moreover, cost estimation models are developed. Benefit parameters are also defined for each construction alternative. Finally, a cost-benefit analysis methodology as well as integration of the methodology into the decision-making model are developed and presented.

STANDARDIZING BRIDGE SLIDES

SIBC requires an activity to move a bridge to its final position following the completion of construction. The critical components of SIBC are the temporary substructure, sliding system, transition substructure, and actuation system. Two recent SIBC projects are monitored and construction activities related to the move are documented. The two projects used different sliding and actuation systems and different temporary and transition structures. However, the primary difficulties observed during the move are from the sliding and actuation system.

The M-50 over I-96 bridge pier, supported on a shallow foundation, was instrumented with laser targets, and the movement during slide was measured using a non-contact laser tracker. Pier deformations measured in the transverse direction (normal to sliding direction) reached a magnitude of 0.6 in. Further analysis and observations indicted that the push force of jacks that are equal is not balanced with the resistance force due to friction, and a force couple is created rotating the superstructure and pushing the pier in the transverse direction.

The US-131 over 3 Mile Road Bridge slide-in and vertical jacking processes for permanent bearing installation are simulated. The objective is to evaluate the impact of unequal abutment alignment, unequal friction between sliding surfaces, continuous and discrete sliding, and displacement and force control sliding. Analysis results collaborate with the observations during the bridge slides. The demonstrated analysis capability can be useful in future projects towards standardizing SIBC and SPMT moves.

SUMMARY AND CONCLUSIONS

The project is organized in five tasks: (1) reviewing the ABC activities nationally and monitoring ongoing ABC projects in Michigan, (2) defining scoping parameters for the implementation of SIBC and SPMT moves, (3) reviewing and evaluating substructure construction and upgrades, and constructability of deep foundations while an existing bridge is in service, (4) developing cost-benefit analysis methodologies for SIBC, SPMT moves, and foundation construction, and (5) developing recommendations to improve SIBC implementations.

The framework of Mi-ABCD is expanded to incorporate SIBC and SPMT move activity parameters; yet the original structure of the framework is maintained. The parameters specific to SIBC and SPMT moves are incorporated under the (1) site and structure considerations (S&ST), (2) cost, (3) work zone mobility (WZM), (4) technical feasibility and risk (TF&R), (5) environmental considerations (EC), and (6) seasonal constraints and project schedule (SC&PS) major parameters. The next version of Mi-ABCD will include the ability to compare the construction delivery alternatives between SPMT moves, SIBC, CC, and PBES for a specific site.

The state-of-the-art and practice related to foundation types, foundation implementation while the existing structure is in service, advantages and difficulties of using specific foundation types under given constraints, and impact of foundation installation on the stability of the existing foundations are synthesized. A foundation type classification is developed based on the degree of disturbance to the surrounding soil during foundation installation. Additionally, a scoping flowchart is developed and presented for foundation reuse, retrofit, or replacement decisions. Lastly, foundation types appropriate for installation while an existing bridge is in service are presented; and conceptual examples of foundation reuse, retrofit, and replacement are included.

A cost-benefit analysis methodology for ABC is developed. Additional costs related to ABC methods are identified after reviewing 123 completed ABC projects. In addition to user cost savings, a list of quantifiable benefits is developed. These benefits are economic impact to nearby businesses and surrounding communities, seasonal limitations, work zone risk to traffic, and site condition complexities. These benefits are represented by quantitative and qualitative parameters. The quantitative parameters include maintenance of traffic (MOT), user, and life-cycle costs. These costs contribute to benefits because of short work-zone construction duration and anticipated long-term durability performance of ABC. After a careful analysis of these quantitative and qualitative parameters, a cost-benefit analysis methodology is developed. The next version of Mi-ABCD will include the ability to evaluate the bridge construction alternatives and may include the costs and benefits associated with each alternative.

In 2014, three Michigan bridges were replaced using SIBC. The construction activities of these two projects are documented. During slide operations, several difficulties specific to the sliding mechanisms are documented. A finite element simulation of the bridge slide of US-131 NB over 3 Mile Road is performed. Also, pier movements were monitored during M-50 over I-96 bridge superstructure sliding. Subsequent analysis of data indicated unexpected forces acting on the pier during slide. The observations from the two projects, pier movement monitoring and subsequent analysis results, and finite element simulation results are used to develop recommendations to improve the SIBC process.

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1 INTRODUCTION

1.1 OVERVIEW

The Michigan Department of Transportation (MDOT) is implementing several accelerated bridge construction (ABC) projects. During the scoping process, MDOT evaluates every bridge project to identify the most suitable construction alternative among conventional construction (CC) and ABC. As ABC methods, prefabricated bridge elements and systems (PBES), slide-in bridge construction (SIBC), and self-propelled modular transporter (SPMT) moves are considered. ABC projects completed and being implemented include prefabricated bridge elements and systems (PBES) and slide-in bridge construction (SIBC).

The first phase of the project on ABC, entitled *Improving Bridges with Prefabricated Precast Concrete Systems* (MDOT RC-1602) (Aktan and Attanayake 2013), developed recommendations towards standardizing PBES by classifying elements, systems, and connections for Michigan. The project also developed a decision-making tool (Mi-ABCD) for comparing ABC vs. CC alternatives for a specific site. The current project was initiated to advance the accelerated bridge construction by developing scoping guidelines for all ABC alternatives, standardizing the operations for bridge slides, and developing guidelines for building foundations while the existing bridge is in service.

1.2 OBJECTIVES AND TASKS

This project is planned to document, evaluate, and verify procedures of bridge replacement utilizing slides and SMPT moves with the goal of leveraging best practices for MDOT implementations and addressing the following three goals:

1) Deciding upon the most suitable accelerated bridge replacement option for a specific site
2) Standardizing activities and associated operations of bridge slides and SPMT moves
3) Developing recommendations for suitable foundation types and methods of construction while the existing bridge is in service.

The specific objectives of the study are as follows:

- Review the ABC activities nationally and monitor ongoing ABC projects in Michigan.

- Define scoping parameters for the implementation of SIBC and SPMT move.
- Review and evaluate substructure construction and upgrades, along with constructability of deep foundations while the existing bridge is in service.
- Develop methodologies for cost calculations associated with SIBC, SPMT moves, and foundation construction.
- Develop recommendations that will help with SPMT moves and SIBC implementations.

To achieve the objectives, the project is organized around the following four tasks:

I. State-of-the-Art and State-of-the-Practice Literature Review: The data and literature collected and synthesized here will support all objectives.

II. Scoping Guidelines for ABC Implementation with Focus on SPMT moves and Slides: The Michigan Specific ABC Decision-Making framework will be extended to include bridge slides and SPMT moves along with PBES and CC based on site-specific data.

III. Methodologies for Design and Construction of Bridge Foundations while Existing Bridge is in Service: A compilation of potential foundation replacement methodologies and associated evaluation framework will be developed.

IV. Cost Analyses for Costs and Benefits Associated with ABC Activities: The existing cost analyses models that include life-cycle cost (LCC) models in the Michigan Specific ABC Decision-Making framework will be extended to include cost estimates for activities involved in bridge slides and SPMT moves. The goal is to develop a cost analysis procedure model that is robust and can be updated as uncertainties of specific cost categories are reduced.

1.3 REPORT ORGANIZATION

This final report is organized into 8 chapters.

Chapter 1 includes the introduction and overview of the research project.

Chapter 2, literature review, provides a list of ABC projects that were obtained from the Federal Highway Administration (FHWA) repository and analyzed for a detailed understanding of specific ABC activities. Additionally, a list of ABC projects that are not included in the FHWA repository are also analyzed. The information related to these additional projects was obtained from the respective agencies. This chapter also describes the resources and summary of methodologies required for developing the content for Chapters 3, 4, 5, and 6.

Chapter 3 presents the framework for deciding upon ABC implementation at a specific site. The framework is expanded from the previous project to incorporate parameters related to SIBC and SPMT move activities.

Chapter 4 describes methodologies for design and construction of foundations while the bridge is in service. The methodologies are developed from an exhaustive literature review of bridge and other civil engineering projects with similar constraints as the ABC. Some benefits of ABC are observed when foundation construction is performed while the old structure is in service. This chapter will present an overview and limitations of constructing a foundation within the vicinity of an existing structure.

Chapter 5 provides a cost and benefit analysis procedure model for ABC alternatives. ABC implementations obviously carry a higher initial cost. The initial cost activities specific to SIBC include temporary structures, equipment and accessories, and slide operations. The SPMT move-specific initial costs include specialty equipment/contractor, mobilization cost, along with travel path and staging area preparation cost. The benefits are often represented as user cost. A more comprehensive review indicates other benefits such as economic impact to nearby businesses and surrounding communities, seasonal limitations, work zone risk to traffic and site condition complexities. This chapter will provide a comprehensive overview of costs and benefits. It also provides cost analysis and models to account for the costs and benefits.

Chapter 6 includes analysis and recommendations for the standardization of bridge slides. The components of this chapter include a detailed review of the activities and implementations related to the two recent MDOT SIBC projects. The chapter also includes the analysis related to the monitoring of the M-50 bridge pier during the move. The simulations of the move of the US-131 over 3 Mile Road bridge primarily show the capability that can be useful in the future for implementation on complex projects. The simulations are also performed to bring clarity and solutions to the reasons of lateral drift of the superstructure during the move. Dynamic effects and substructure loads are also an outcome of the simulations.

Chapter 7 provides a summary and conclusions related to the project tasks.

Chapter 8 includes the reference list.

2 STATE-OF-THE-ART AND STATE-OF-THE-PRACTICE LITERATURE REVIEW

2.1 OVERVIEW

FHWA has developed a web-based repository for ABC projects in the US. The FHWA repository (FHWA 2015) website consists of folders for several states that have implemented ABC projects. Each project folder consists of sub-folders that may include photos, contract plans, specifications, bid tabs and other related information. This repository was used as a source of information related to ABC projects. The information and data on ABC projects outside the FHWA repository were obtained primarily from the respective DOT websites. Project data is obtained by contacting respective DOT personnel. As of April 2015, a total of 123 ABC projects were compiled including 76 PBES, 30 SIBC, and 11 SPMT moves (Table 2-1). These project documents provide information about ABC methodology, temporary structure design, sequence of ABC operations, constructability challenges, scoping parameters, foundation types, and cost.

Table 2-1. Completed ABC Projects in the US

No.	Project Name	State	ABC Methodology
1	Grayling Creek Bridge	Alaska	PBES
2	O'Malley Bridge	Alaska	PBES
3	Kouwegok Slough Bridge	Alaska	PBES
4	Pelican Creek Bridge	Alaska	PBES
5	Oak Creek Bridge	Arizona	SIBC
6	Mescal Road/ J-Six Ranch Bridge	Arizona	PBES
7	Hardscrabble Creek Bridge	California	SIBC
8	I-40 Bridges	California	PBES
9	Hilltop Drive Overcrossing	California	PBES
10	San Francisco Yerba Buena Island Viaduct	California	SIBC
11	Russian River Bridge	California	PBES
12	Craig Creek Bridge	California	PBES
13	Maritime Off-Ramp Bridge at I-80 & I-880	California	SPMT Move
14	Carniquez Strait Bridge	California	Longitudinal Launching
15	SH 66 over Mitchell Gulch	Colorado	PBES
16	SH 71 ML over Ft Lyon Canal	Colorado	SIBC
17	SH 266 ML over Ft Lyon Storage Canal	Colorado	SIBC
18	SH 266 ML over Holbrook Canal	Colorado	SIBC
19	US-34 over Republican River	Colorado	SIBC
20	Church Street Bridge (Truss)	Connecticut	High-Capacity Crane Lift
21	I-10 Bridge over Escambia Bay (Replacement Bridge)	Florida	PBES
22	I-10 Bridge over Escambia Bay	Florida	High-Capacity Crane Lift
23	Graves Avenue Bridge	Florida	SPMT Move
24	Kia Blvd Bridge	Georgia	PBES
25	Keaiwa Stream Bridge	Hawaii	PBES
26	South Punaluu Stream Bridge	Hawaii	PBES

27	North Kahana Stream Bridge	Hawaii	PBES
28	Vista Interchange Bridge	Idaho	PBES
29	Black Cat Road Bridge	Idaho	PBES
30	Illinois Route 29 Bridge over Sugar Creek	Illinois	PBES
31	Milton-Madison Bridge	Indiana	SIBC
32	Sedley Bridge	Indiana	PBES
33	US 6 over Keg Creek Bridge	Iowa	PBES
34	Little Cedar Creek Bridge	Iowa	PBES
35	640th Street over Branch Racoon River Bridge	Iowa	PBES
36	Jakway Park Bridge	Iowa	PBES
37	Madison County Bridge	Iowa	PBES
38	24th Street Bridge over I-29/I-80	Iowa	PBES
39	Mackey Marsh Rainbow Arch Bridge	Iowa	PBES
40	Massena Bridge	Iowa	SIBC
41	UPRR Bridge	Kansas	PBES
42	US 27 Bridge over Pitman Creek	Kentucky	PBES
43	LA 3249 (Well Road) Bridge	Louisiana	SPMT Move
44	I-10 Bridge over Lake Pontchartrain (original Twin Spans)	Louisiana	High-Capacity Crane Lift
45	Boothbay Bridge	Maine	PBES
46	Littlefields Bridge	Maine	SIBC
47	MD Route 24 Bridge over Deer Creek (Rocks Steel Truss Bridge)	Maryland	PBES
48	MD 28 over Washington Run Creek Bridge	Maryland	PBES
49	MD 450 over Bacon Ridge Branch Bridge	Maryland	PBES
50	MD Route 362 over Monie Creek Bridge	Maryland	PBES
51	Cedar Lane Bridge	Maryland	PBES
52	Cedar Street Bridge (Wellesley)	Massachusetts	SPMT Move
53	Phillipston Bridge	Massachusetts	SPMT Move
54	Parker River Bridge	Massachusetts	PBES
55	Salem Street Bridge Eastbound (93Fast14)	Massachusetts	PBES
56	Uxbridge –River Road Bridge over Ironstone Brook	Massachusetts	PBES
57	Parkview Avenue Bridge	Michigan	PBES
58	M-50 over I-96	Michigan	SIBC
59	US-131 over 3 Mile Road	Michigan	SIBC
60	TH 53 Bridge over Paleface River	Minnesota	PBES
61	TH 61 Bridge over Gilbert Creek	Minnesota	PBES
62	Larpenteur Ave Bridge	Minnesota	SIBC
63	Kickapoo Bridge	Mississippi	PBES
64	I-44 Bridge over Gasconade River	Missouri	SIBC
65	I-70 / Lake St. Louis Boulevard Bridge	Missouri	PBES
66	Mill Street Bridge	New Hampshire	PBES
67	I-93 Bridge over Loudon Road (Route 9)	New Hampshire	PBES
68	Route 202 Bridge over Passaic River	New Jersey	PBES
69	Route 70 Bridge over Manasquan River	New Jersey	PBES
70	Route 1 Bridges over Olden Ave.& Mulberry Street	New Jersey	PBES
71	Gordon's Corner Road Bridge over Route 9	New Jersey	PBES
72	Broadway Bridge over Little Timber Creek	New Jersey	PBES
73	Willis Avenue Bridge over Harlem River	New York	SPMT Move
74	Belt Parkway Bridge	New York	PBES
75	I-84 over Dingle Ridge Road	New York	SIBC
76	West Mesquite Interchange at 1-15	Nevada	SIBC
77	US 17 Bridge over Tar River	North Carolina	PBES
78	NC 12 Bridge over Molasses Creek	North Carolina	PBES

79	Beaufort and Morehead Railroad Trestle Bridge	North Carolina	PBES
80	Biltmore Avenue Bridge	North Carolina	PBES
81	Linn Cove Viaduct	North Carolina	PBES
82	Bowman Road Bridge	Ohio	PBES
83	U.S. Route 22 Bridge	Ohio	PBES
84	Cotton Creek Bridge	Oklahoma	SIBC
85	OR-213 Bridge over Washington Street	Oregon	SIBC
86	Depot Street Bridge	Oregon	SIBC
87	Volmer and Johnson Creek Bridges	Oregon	PBES
88	Kimberly Bridge	Oregon	PBES
89	Imnaha Bridge over Little Sheep Creek	Oregon	SIBC
90	Elk Creek Bridge (Crossing No. 3)	Oregon	SIBC
91	Fremont Bridge	Oregon	PBES
92	US 26 Bridge over Mill Creek	Oregon	PBES
93	OR 47 Bridge over Dairy Creek Overflow	Oregon	PBES
94	Sauvie Island Bridge	Oregon	SPMT Move
95	OR-213 Jughandle	Oregon	SIBC
96	Montour Run Bridge No. 6	Pennsylvania	High-Capacity Crane Lift
97	Ben Sawyer Swing Bridge	South Carolina	SIBC
98	Buffalo Creek Bridge	South Dakota	PBES
99	41st Street Bridge	South Dakota	PBES
100	SH 290 Bridge over Live Oak Creek	Texas	PBES
101	State Highway 36	Texas	PBES
102	Fredericksburg Road Bridge	Texas	SIBC
103	I-215 / 4500 South Bridge	Utah	SPMT Move
104	Riverdale Road Bridge over I-84	Utah	PBES
105	I-15 / Layton Parkway Bridge	Utah	Longitudinal Launching
106	I-15 / Pioneer Crossing Bridge	Utah	SPMT Move
107	I-15 / Sam White Lane Bridge	Utah	SPMT Move
108	I-80 Bridge over 2300 East	Utah	SIBC
109	I-70 Bridge over Eagle Canyon (Eastbound)	Utah	PBES
110	I-84 Bridge F-114	Utah	PBES
111	I-80 at Summit Park	Utah	SIBC
112	I-80 at Wanship	Utah	SIBC
113	Route 4 Bridge 50 over Ottauquechee River (Woodstock)	Vermont	PBES
114	Chester Vermount Bridge	Vermont	PBES
115	I-405 / Northeast 8th Street Bridge	Washington	SIBC
116	I-5 / South 38th Street Bridge	Washington	PBES
117	Lewis and Clark Bridge (Truss)	Washington	SPMT Move
118	I-5 / US 12 Bridge at Grand Mound	Washington	PBES
119	Hood Canal Bridge	Washington	SIBC
120	Eastern Avenue Bridge	Washington D.C.	PBES
121	CTH B Bridge over Parsons Creek	Wisconsin	PBES
122	WIS 29 EB Bridge	Wisconsin	SIBC
123	Inyan Kara Creek Bridge	Wyoming	PBES

2.2 PROJECT SCOPING PARAMETERS

A multi-criteria decision-making framework was developed by Aktan and Attanayake (2013) to comparatively assess CC vs. ABC, and it was presented in the MDOT report RC-1602. The decision- making framework is customized for implementation in Michigan. A guided software program and a user manual were developed and titled Michigan Accelerated Bridge Construction Decision-Making (Mi-ABCD) tool. In the current version of Mi-ABCD (version 2.0), the ABC only reflects PBES as a project delivery alternative. However, new ABC technologies, such as SPMT moves and SIBC, are being increasingly implemented throughout the U.S.

The information collected from the projects listed in Table 2-1 and the MDOT report RC-1602 by Aktan and Attanayake (2013) are analyzed to develop a list of preliminary scoping parameters. Following input from the Research Advisory Panel, parameters are finalized and arranged in a hierarchical order. These parameters will be the basis for evaluating CC, PBES, SPMT moves and SIBC project delivery alternatives for a given site. Further, the scoping parameters are grouped into major parameters and associated sub-parameters. The sub-parameters are again grouped into secondary level sub-parameters. Sub-parameter grouping allow detailed parameter consideration to determine a methodology within ABC. Moreover, the associated quantitative data and qualitative data are identified. A detailed description of the scoping parameters and the decision-making framework is presented in Chapter 3.

2.3 FOUNDATIONS FOR ABC

The objective of the review presented in this section is to identify suitable foundation types and methods of construction while the existing bridge is in-service. Hence, this section presents (a) a brief overview of the foundation types, (b) foundation types implemented in ABC projects, (c) a summary of the foundation policies implemented by a number of selected highway agencies, (d) a few ABC projects where foundations were constructed while the bridge was in service, and (e) a few case studies, other than ABC projects, where foundations were constructed under highly constrained conditions.

2.3.1 Foundation Types

Foundations are broadly classified as shallow and deep (Coduto 2001). Deep foundations are driven piles, drilled shafts, auger piles, and micropiles. Depending on the amount of disturbance to the surrounding soil during foundation installation, construction method or foundations types are also classified as non-displacement, low displacement, and high displacement. Examples of non-displacement are shallow foundations, drilled shafts, continuous flight auger piles, and drilled cast-in-place micropiles. Examples of low displacement are H-piles and pile driven in predrilled or jetted holes. Precast concrete piles and driven closed-ended pipes are two examples of high displacement types.

2.3.1.1 Driven Piles

Driven piles are the most commonly used deep foundations. Among this category the most utilized are the steel piles: H-piles and steel pipe piles. Typical H-pile sizes are 12 in. and 14 in. Pipe pile diameter ranges from 14 in. to 30 in. H-piles usually have better drivability than pipe piles. However, pipe piles have a higher lateral load capacity and are easier to design for bridges with high-skew angles.

Typically, piles are driven by using an impact or vibratory hammer. Vibration due to pile driving can cause ground settlements and deformations that may lead to differential settlements of foundations and deformations or cracking of underground utilities (Zekkos et al. 2013). The vibration induced by the pile driving operation near an existing foundation is the major concern when driven piles are considered for ABC.

In the pile driving operation, according to Buehler (2004), the peak particle velocity (PPV) is generally accepted as the most appropriate descriptor for evaluating the potential for structural damage. In order to prevent vibration-induced damage to retaining walls and bridges, the Swiss Association of Standardization recommends limiting PPV to 0.5 in/sec. Other studies have suggested that limiting PPV up to 2 in/sec will control damages to bridges (Buehler 2004).

In general, structures located more than 80 ft from pile driving operations may be outside the structural damage zone even in the loosest fills. Picornell and Monte (1985) determined that the ground movements induced by pile driving drops to near zero at a distance of about 39 ft from the driven pile. Dalmatov et al. (1968) indicated that the ground movements were near zero at a distance of 26 ft from the driven pile.

Zekkos et al. (2013) evaluated pile driving vibrations by monitoring five sites in Michigan. The outcome of this study is a spreadsheet to estimate PPV and several other parameters.

Application of this spreadsheet is limited by soil profile data used in calibrating the prediction models used in the spreadsheet. Even though PPV of 2 in/sec is used by various agencies as the threshold, an existing bridge and earth retaining structures may receive damages at lower PPV values depending on the site and structural conditions. As a preventive measure, monitoring of the existing bridge and earth retaining structure's response is recommended when driven piles are installed using impact hammers.

According to Buehler (2004), the following methods can be used to reduce vibration induced by driven pile installation to an acceptable level:

- Jetting
- Predrilling
- Using pile cushioning
- Using nonimpact drivers
  - Hydraulically operated static pile drivers
  - A resonance-free or variable eccentric moment vibratory pile driver.
  - Tubex piles: consist of a steel pipe casing attached to a drill tip. The pipe is installed by applying a torque as well as a constant vertical force. The casing is used as a lining for concrete or grout that is placed after the steel tube lining is installed. Steel pipe is a structural element and increases lateral load capacity. The drill tip is primarily used for pile installation. It also consists of ports to inject grout to produce a soil-cement mixture around the pile. This pile type can be installed in confined areas. According to http://www.foundationpiledriving.com/, Tubex piles have been installed with a headroom as low as 10.5 ft. According to Buehler (2004), this specific pile type has induced a peak amplitude of 0.05 in/sec at 25 ft, which is much smaller than the damage thresholds set by various agencies.

Table 2-2 shows the advantages and limitation of using the driven piles.

Table 2-2. Advantages and Limitations of Driven Piles

Advantages	Limitations
Pile can be inspected before it is driven into the ground.	Driving activity might exceed both noise and vibration limits.
Construction procedure is unaffected by ground water table.	Low headroom is a constraint.
Piles can be spliced and driven into deeper strata.	Pile size is limited.
Driven pile foundations are generally less expensive than drilled shafts.	

2.3.1.2 Drilled Shafts

Typically, drilled shafts are used at sites where driven piles are not economical due to large loads. Drilled shafts are also used when pile driving vibrations are a concern. The size of drilled shaft ranges from 3 ft to 10 ft in diameter. The length of drilled shafts can be up to 200 ft. However, lengths over 100 ft require special drilling equipment (MDT 2002). Figure 2-1 shows a typical construction process (Brown et al. 2010).

Drilled shafts can be designed to carry large axial and lateral loads (moments). It is possible to install a drilled shaft outside the existing bridge footprint as shown in Figure 2-2. Drilled shafts can also be constructed with limited headroom (Figure 2-3). These are favorable features for ABC where foundation construction is expected to be completed while the existing bridge is in service. Table 2-3 shows the advantages and limitations of drilled shafts.

Figure 2-1. Construction of drilled shaft in dry, cohesive soils (Brown et al. 2010)

Figure 2-2. Drilled shaft construction outside the bridge footprint (Brown et al. 2010)

Figure 2-3. Drilled shaft installation under a bridge (Brown et al. 2010)

Table 2-3. Advantages and Limitations of Drilled Shafts

Advantages	Limitations
Suitable for a wide range of ground conditions	Requires an experienced and capable contractor; usually a specialty subcontractor.
Suitable for large axial as well as lateral loads	Batter piles are not possible.
Single shaft can be used without a pile cap when space is constrained due to existing structures or foundations.	May not be efficient in deep soft soils without a suitable bearing formation.
Low noise and vibration levels.	Might require specialized equipment for special installations.
Can be constructed with limited headroom (25 ft or less).	Construction is sensitive to groundwater or challenging drilling conditions.
	Construction quality control and quality assurance is a challenge.
	It is challenging and costly to repair defects.

2.3.1.3 *Continuous Flight Auger (CFA) Piles*

A CFA pile construction uses a hollow-stem auger to drill down to the desired depth. As the auger is withdrawn, sand-cement grout or concrete is pumped into the hole to form a cast-in-place column. A steel reinforcement cage is inserted into the fresh concrete or grout if required by the design. The construction process is shown in Figure 2-4. The diameter of a pile ranges from 12 to 36 in., and the depth can range from 60 to 70 ft (SHRP 2012).

CFA piles are preferred if no headroom restrictions exist at the site. However, the state-of-practice shows that CFA piles can also be implemented in low headroom conditions. Low headroom requires segmental addition of augers, which makes continuous grouting a challenging task during an auger withdrawal. Other challenges include the presence of rocks and boulders, shallow groundwater table, and need for containment systems to control debris and grout spills. Figure 2-5 shows the segmental construction of a CFA pile with a low headroom rig. Low headroom requires a segmental addition of augers, which make the continuity of grouting process during an augers withdrawal a challenging task. Grouting pressure needs to be closely monitored and a diameter less than 18 in. is preferred. Even though it is challenging, batter piles can also be constructed (Brown et al 2007). Table 2-4 lists the advantages and limitations of using CFA piles.

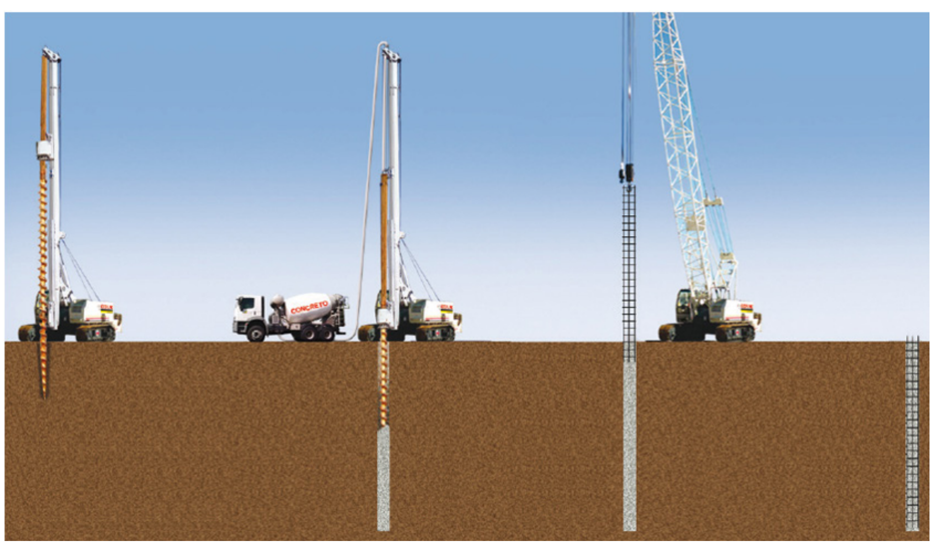


Figure 2-4. CFA pile construction process (Especiais 2014)

Figure 2-5. Low headroom rig with segmental augers (Brown et al. 2007)

Table 2-4. Advantages and Limitations of CFA Pile Foundations

Advantages	Limitations
Rapid installation	Not suited for soils with rocks and boulder.
Limited noise and vibration	Groundwater should be very deep.
Possible, but challenging to install under low headroom	Specialized equipment is required.
Applicable in weak soils	Procedures have not been fully developed.
	Need containment systems to control debris and grout spills
	Drilling may reduce the confinement of the neighboring piles.
	Construction quality control and quality assurance is a challenge.
	It is challenging and costly to repair.

2.3.1.4 Micropiles

Micro-piles are installed by using driving, jacking, or drilling methods. The driven micro-piles are constructed by driving a heavy wall steel open or closed-end pipe to a predetermined depth or to a predetermined driving resistance. The closed-end pipe is later filled with cement grout. If using jacked micro-piles, the construction method is similar to driven micro-piles, except the pipes are installed by placing hydraulic jacks between the pipe and a reaction weight (typically the existing structure) and pushing sections of pipes into the ground. The ultimate capacity of the pile is limited by the reaction weight. Drilled cast-in-place (D-CIP) micro-pile construction is similar to the construction of drilled shafts. A hole is drilled using solid or hollow augers (i.e., dry drilling), a drill bit or heavy walled casing with a cutting edge (i.e., wet drilling), or a combination thereof. A steel reinforcing member, typically a high strength threaded steel bar connected with couplers, is installed into the hole prior to grouting. A permanent steel casing can be used in combination with the steel reinforcing member to provide additional lateral as well as axial capacity (Rabeler et al. 2000). Figure 2-6 shows the construction procedure of a drilled cast-in-place (D-CIP) micropile. Figure 2-7 shows the typical cross-sections of D-CIP micropiles.

Micropile capacity depends on the subsurface conditions and the structural capacity of the pile, which depends on the pile size and yield strength of the structural steel member. The typical diameter of a micropile ranges from 6 to 9 in. (Rabeler et al. 2000). End bearing and side friction define micropile load bearing capacity. Rabeler et al. (2000) suggests using the values shown in Table 2-5 as preliminary design values when the competent material layers are within a reasonable depth. It is acknowledged that the actual capacity depends on the site-specific conditions, and pile size and depth. Micropile capacity can be increased by embedding the pile into dense/hard soil or rock or by using enlarged bases. The pile base can be enlarged by using grout bulbs that can be formed by pressure grouting through the pipe or with the use of a small explosive charge. Bulb diameter ranges from 12 to 24 in. Buckling of micropiles needs to be considered because of their slenderness (Sabatini et al. 2005). Micropiles have a limited lateral load capacity; hence, the piles are installed in an angle (batter piles) to enhance the lateral load capacity.

Table 2-5. Range of Micropile Design Capacities (Rabeler et al. 2000)

Bearing Material	**Typical Design Capacities, kips (kN)**
Stiff to hard clay	7.9 to 20.2 (35 to 90)
Medium to dense sand	20.2 to 67.4 (90 to 300)
Very dense sand/till	39.3 - 157.4 (175 to 700)
Weathered to competent rock	101.2 – 202.3+ (450 to 900+)

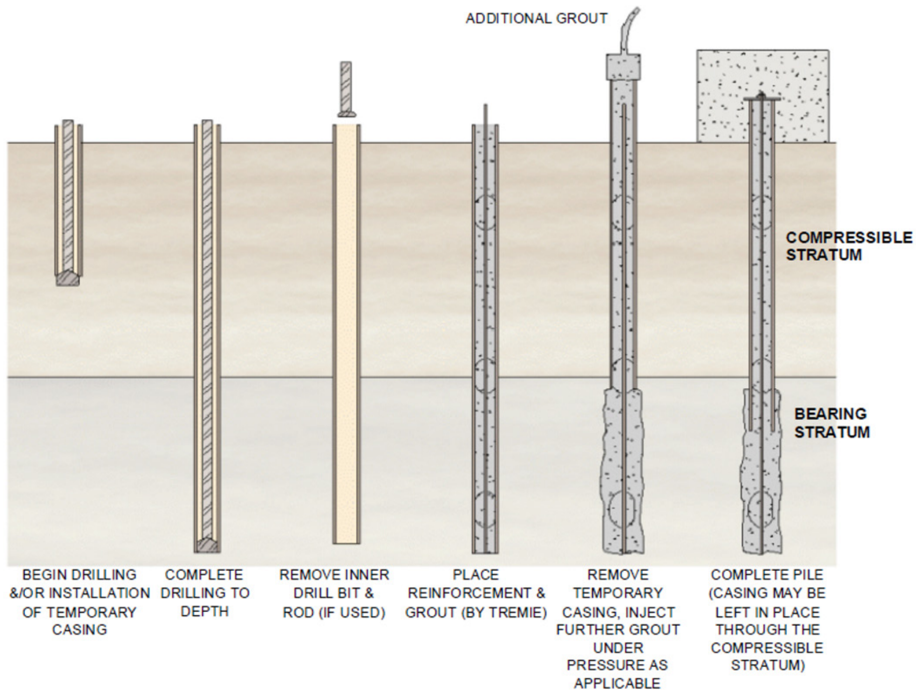


Figure 2-6. Drilled cast-in-place micropile construction sequence (Sabatini et al. 2005)

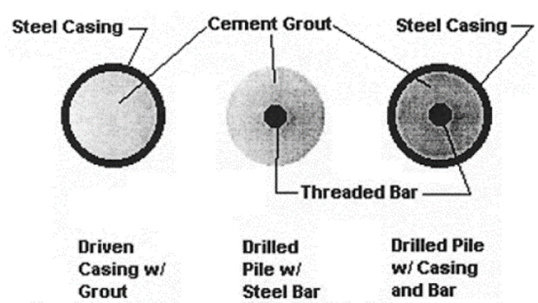


Figure 2-7. Typical drilled cast-in-place micropile sections (Rabeler et al. 2000)

The cost of micropiles usually exceeds conventional piling systems, especially driven piles. However, under certain combinations of circumstances, micropiles will be the cost-effective option, and occasionally will be the only feasible constructible option (Armour et al. 2000). Micropile installation usually requires about 10 to 12 feet of headroom. Advantages and limitations for micropile foundation are presented in Table 2-6.

Table 2-6. Advantages and Limitations of Using Micropiles for Bridge Foundations

Advantages	Limitations
The equipment is relatively small and can be mobilized in restrictive areas	Vertical micropiles are limited in lateral load capacity.
Can be installed in all ground conditions	More expensive than other options
Cause minimal disturbance to adjacent structures	
Cause minimal noise and vibration	
Can be used in low head room conditions (6 ft minimum)	
Can be used for underpinning existing foundations	
Can be installed as batter piles	

2.3.1.5 *Shallow Foundations*

Spread footings are placed on competent natural soils, improved soils, and engineered fill materials (Samtani et al. 2010). According to DiMillio (1982), cost of the spread footings used in three bridges constructed by the Washington State Department of Transportation (WSDOT) was 46% to 67% less expensive than the deep foundation alternative.

Construction does not require excessive headroom. Also, noise and vibration are not concerns. Unless site conditions (such as scour, ground water table, incompetent soil strata, alignment of existing and new bridge footprint, available space, etc.) demand for a different foundation type, shallow foundations are a good option to construct the foundations while the bridge is in service (FHWA 2013c). Table 2-7 lists the conditions that need to be considered when evaluating a site for spread footing.

Table 2-7. Conditions that might Limit or Eliminate the Use of Spread Footings (Samtani et al. 2010)

Conditions that make the use of spread footing not feasible	Conditions that might limit the use of spread footing
• Stream crossings where scour is a concern • Liquefiable soils • Deep collapsible soil deposits • Soils with swell pressure larger than footing pressure • Karstic deposits • Deep frost penetration • Areas of tidal fluctuations • Possibility of future unsupported excavations below the base of the footing • Significant long-term settlements that would affect the structural integrity of the bridge	• Limited right-of-way which would control the size of the footing • Excavation of contaminated soils • Significant dewatering for cases where the water table is within the depth of embedment • Situations where groundwater may rise within the depth of significant influence in the future

2.3.2 Foundations Implemented in ABC Projects

Foundation types associated with each ABC methodology (PBES, SIBC, and SPMT move) are discussed. The foundation types of ABC projects are compared to the construction method in order to identify similarities between the project characteristics. Additionally, ABC projects are clustered with the foundation types and respective mobility impact times to evaluate the effect of foundation selection and construction process on the work zone traffic. To gauge the effectiveness of ABC, the following two time metrics are used:

1) Onsite construction time: This is the period of time from when a contractor enters the project site location until all construction-related activity is removed. This includes,

but is not limited to, the removal of traffic control markings, signage, devices, equipment, and personnel.

2) Mobility impact time: This includes any period of time when the traffic flow of the transportation network is reduced due to onsite construction activities. FHWA (2013b) categorized the ABC projects in the repository into five tiers based on the mobility impact time of the project as shown in Table 2-8.

Table 2-8. FHWA Categorization for ABC Projects *(*FHWA 2015*)*

Tier	Mobility Impact Time
1	1 – 24 hours
2	1 – 3 days
3	3 days – 2 weeks
4	2 weeks – 3 months
5	More than 3 months

2.3.2.1 Foundation Types and ABC Methodology

When SPMT move and SIBC techniques are implemented, the existing bridge carries traffic until the bridge is closed for superstructure replacement. Sometimes, additional closure time is required when it is difficult to perform foundation and substructure work ahead of bridge demolition. Depending on the duration of traffic disruption, the mobility impact time is defined as shown in Table 2-8. The mobility impact duration can be minimized if methodologies for installing foundations while the existing bridge is in service are developed. This section presents the foundation types used in various ABC projects from the FHWA repository (FHWA 2015) and the associated ABC methodology. Further, mobility impact duration during each project was evaluated, and the results are presented.

2.3.2.1.1 Construction Methodology and Foundation Types

Review of ABC projects from the FHWA repository (FHWA 2015) showed that most of ABC projects were PBES implementations (Figure 2-8). Only a few projects with application of SPMT moves and SIBC were identified. In addition, a few cases of Longitudinal Launching were identified and included in the foundation evaluation. Longitudinal Launching is a placement procedure similar to Slide-In with the difference of sliding the bridge longitudinally (i.e., along the bridge axis) instead of laterally (i.e., transverse to the bridge axis). Table 2-9 presents projects by foundation types according to the ABC methodology.

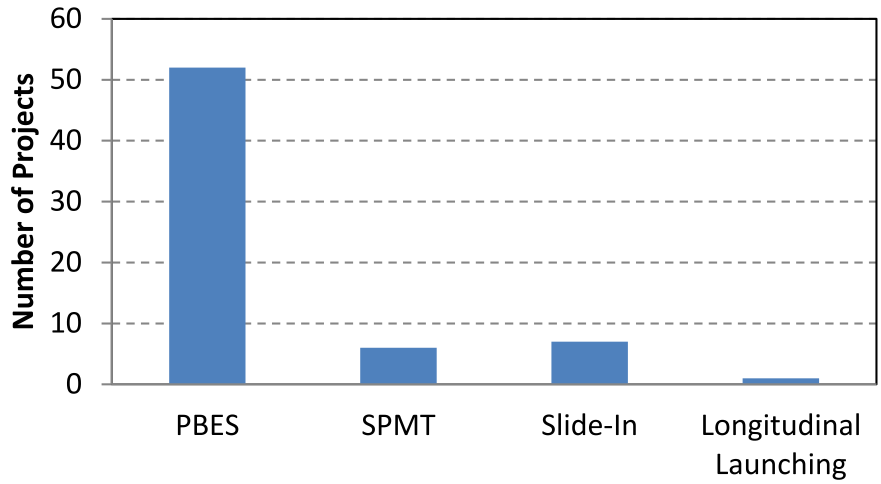


Figure 2-8. ABC projects by construction method

Table 2-9. Foundation Types by Construction Method

Foundation Type / ABC Methodology	Number of Projects with Specific Foundation Type: Micro-pile	Drilled shaft	H-pile	Open-ended pipe pile	Pile driven in pre-drilled hole	Close-ended pipe pile	Precast conc. pile	Mandrel-driven shell pile	Spread footing	Total Projects
PBES	2	4	22	7	1	4	4	2	6	**52**
SPMT Move	0	2	0	0	0	1	1	0	2	**6**
SIBC	0	3	0	1	1	0	0	0	2	**7**
Longitudinal Launching	0	0	0	0	1	0	0	0	0	**1**
Total Projects	**2**	**9**	**22**	**8**	**3**	**5**	**5**	**2**	**10**	**66**

The ABC methodology is directly related to the mobility impact time. In Figure 2-9 to Figure 2-13, the trend indicates that use of SPMT moves is most suitable for Tier 1. As shown in Figure 2-9, one Longitudinal Launching project was completed with a mobility impact of less than 24 hours. For Tier 2, SIBC is the predominant technique followed by SPMT moves (Figure 2-10). For Tier 3, Tier 4, and Tier 5, almost all projects used PBES (Figure 2-11 to Figure 2-13).

With PBES, assembling all bridge elements in less than 3 days is not expected (Tier 1 and Tier 2). However, highway agencies, with cooperation from contractors, have developed construction techniques to reduce traffic disruption. Two PBES projects were completed within a 24-hour window placing them into Tier-1. Another PBES project was completed in less than 3 days, making it Tier-2. Sometimes, staged construction allows a project to be qualified as Tier-1 or Tier-2. As an example, the Riverdale Road Bridge over I-84 in Utah was constructed in two phases: in the first phase two bridges were constructed on either side of the existing bridge, traffic was shifted to the new bridges, the existing bridge was demolished, and the new bridge was constructed in between, joining all three structures to form a wide single bridge.

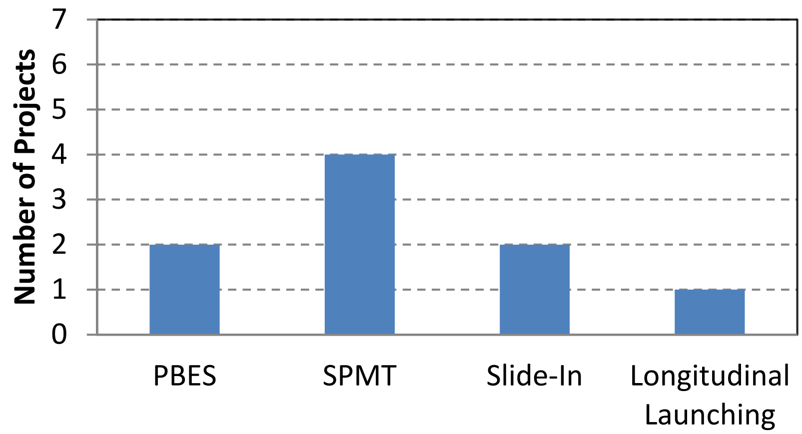


Figure 2-9. ABC methodologies for Tier 1

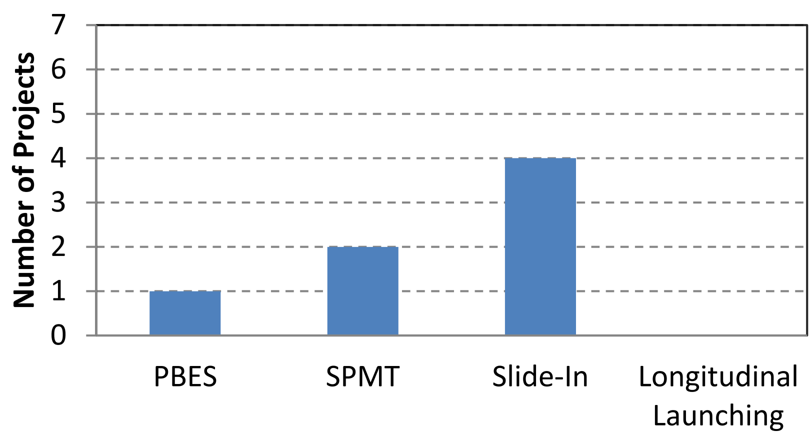


Figure 2-10. ABC methodologies for Tier 2

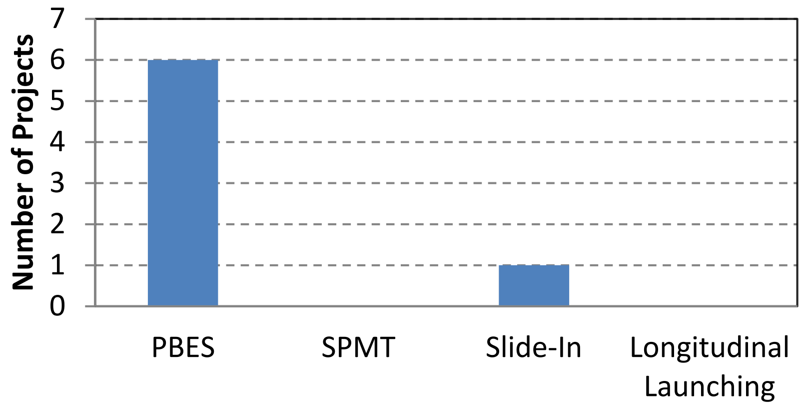


Figure 2-11. ABC methodologies for Tier 3

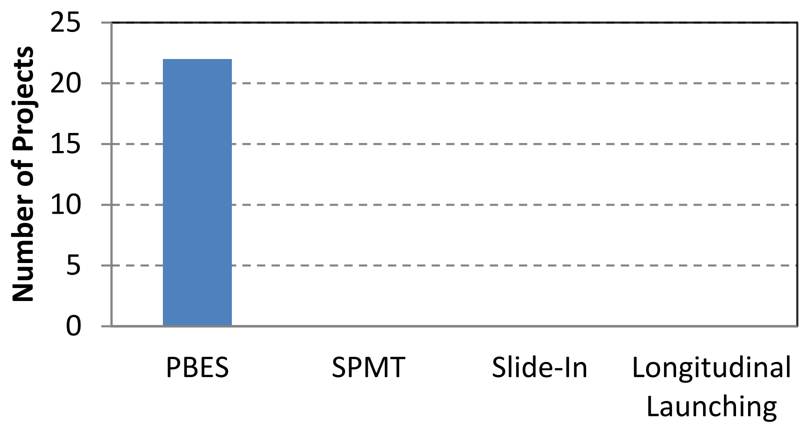


Figure 2-12. ABC methodologies for Tier 4

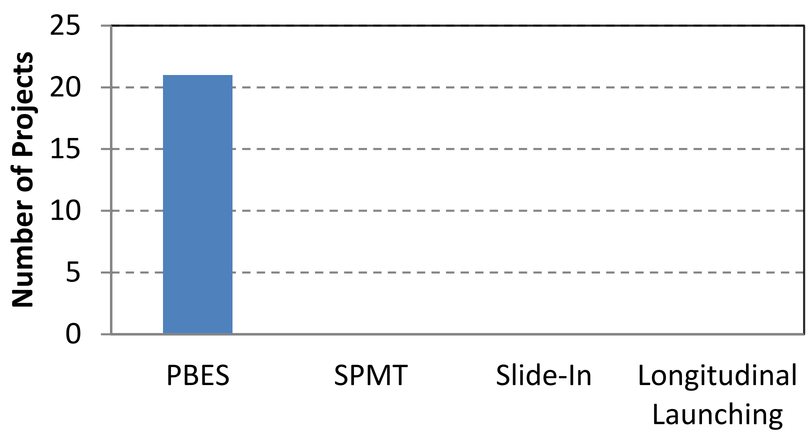


Figure 2-13. ABC methodologies for Tier 5

The ABC methodologies, with respect to the foundation types, are shown in Figure 2-14 through Figure 2-16. As shown in Figure 2-14 and Table 2-9, most PBES projects utilized H-piles. Other methodologies, such as SPMT moves, SIBC, and Longitudinal Launching, used drilled shafts and spread footings (Figure 2-15 and Figure 2-16).

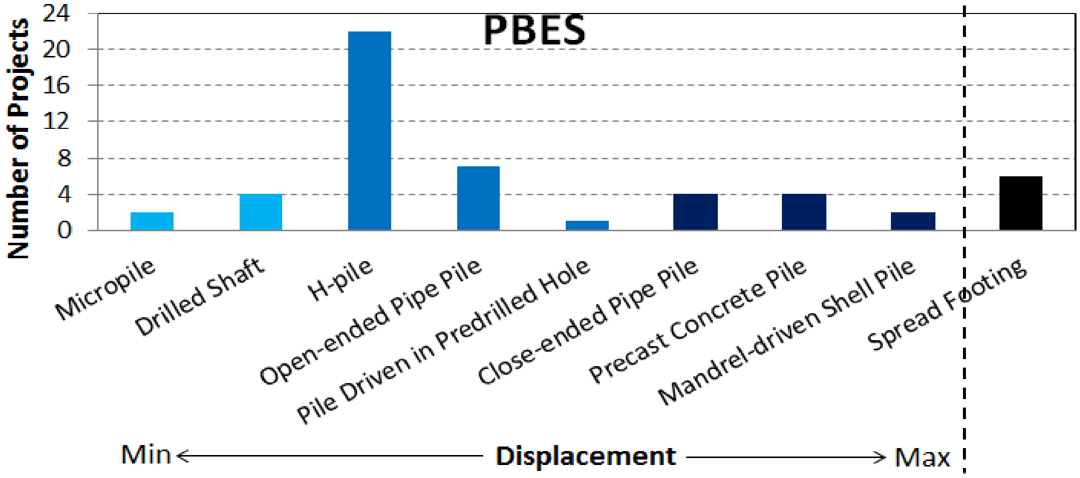


Figure 2-14. Foundation types for PBES

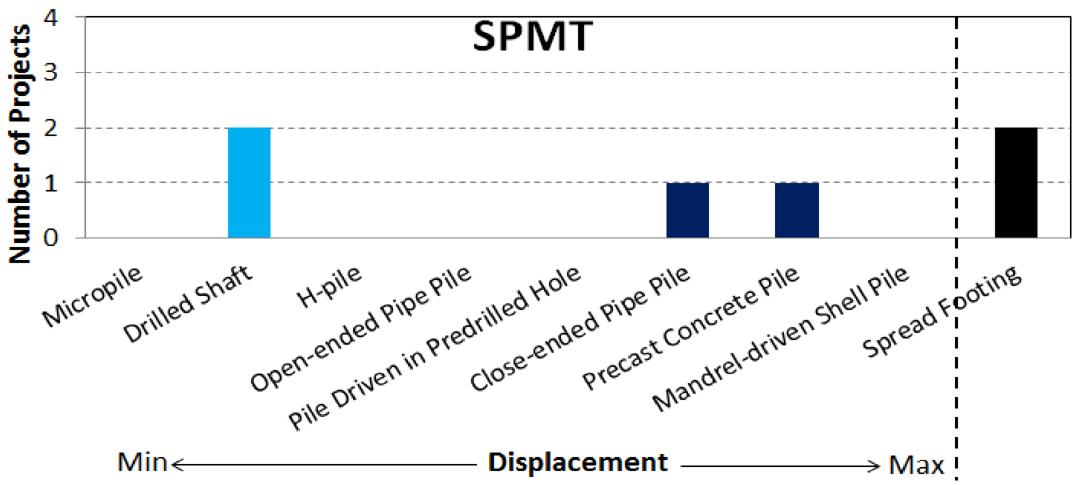


Figure 2-15. Foundation types for SPMT move

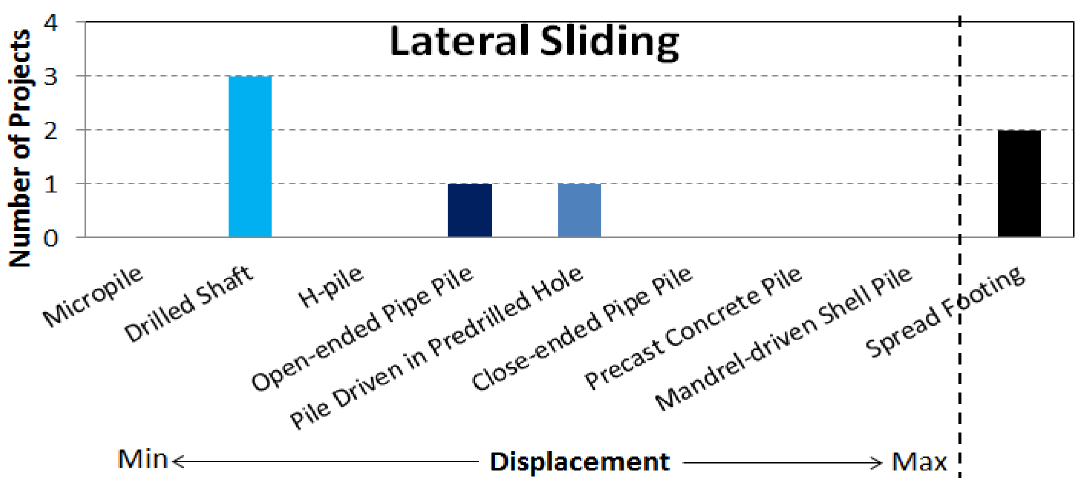


Figure 2-16. Foundation types for SIBC

2.3.2.1.2 Mobility Impact Time and Foundation Types

The ABC projects are grouped according to the foundation type and the mobility impact time. Figure 2-17 shows the foundation types for each Tier. For Tier 1 to 3, only a few ABC projects per foundation type were identified. Except micropiles, open-ended pipe piles, and mandrel-driven shell pile, every other foundation type was used in Tier 1 projects. Also in Tier 2, drilled shaft, H-piles, piles driven in predrilled holes, and spread footings were used. The piles or the footings used in Tier 2 are non-displacement or low displacement types. For Tier 3, three types of driven piles (H-piles, open-ended pipe piles, and precast concrete piles) and spread footings were used. H-piles were the most common foundation type in ABC projects under Tier 4 and Tier 5. Micro piles were used in two Tier 5 projects.

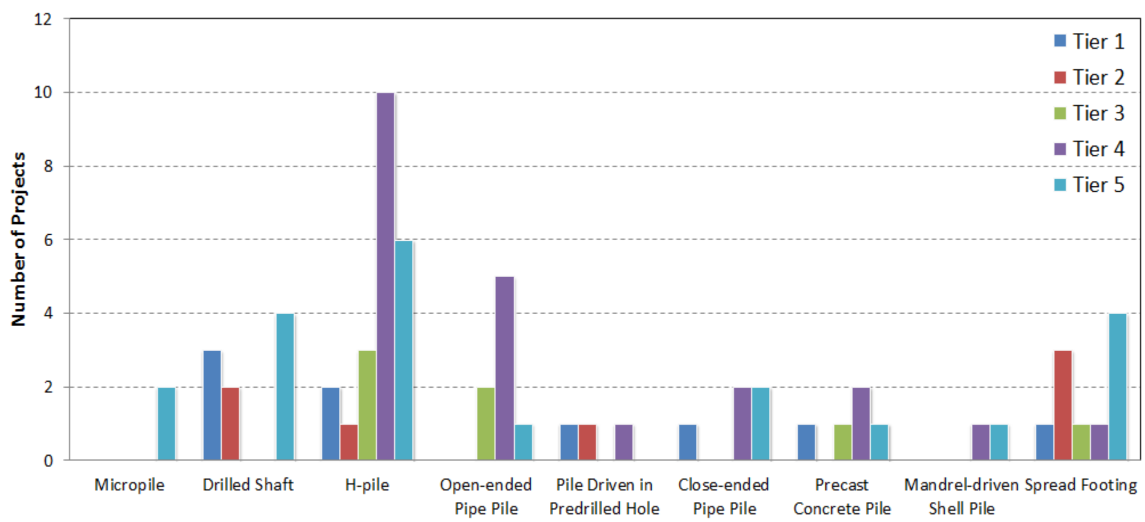


Figure 2-17. Mobility impact time by foundation type

The data is inadequate to make firm conclusions on the foundation types used for each Tier or with a specific ABC method. Hence, foundation policies of a selected number of DOTs were reviewed and presented in Section 2.3.3 to understand if a specific foundation type is favored for a jurisdiction or for a project delivery method. Also, a selected number of ABC project documentation was reviewed to identify the type of foundations and the construction methods utilized to install foundations while the existing bridge was in service. The findings of this review are presented in Section 2.3.4.

2.3.3 State DOT Bridge Foundation Policies

The foundation policies of the states that implemented a large number of ABC projects are discussed in this section. The foundation policies specify the foundation types that a state favors or outlaws and the reason behind the decisions.

2.3.3.1 California Department of Transportation (Caltrans)

The structure foundation investigation is performed at every bridge site to provide preliminary geotechnical design criteria for the design of a new bridge or replacement bridge. An exploratory boring is taken to obtain information on groundwater conditions, allowable capacities, and other data needed to evaluate the selected foundation (SCST 2013). If lacustrine deposits are encountered in the exploratory boring, then the planned structure is proposed to be supported on deep foundations consisting of driven piles. Lacustrine deposits are stiff to very stiff clay with sand and sandy clay. At these bridge sites, if the groundwater table is shallow, then the foundation policy recommends using Class 90 Precast Prestressed Concrete Piles as they are designed for corrosion resistance. Alternatively, the foundation policy allows implementing drilled shafts. Note that the term used by Caltrans for drilled shafts is cast-in-drilled-hole (CIDH) piles. Caltrans mostly uses drilled shafts for the following reasons (Ostrom 2013):

- They can be designed and constructed deep into the bedrock. Although driven piles are simpler and quicker to design, they have limited penetration into the bedrock.
- Construction considerations that favor drilled shafts are noise and vibration.
- At the sites where scour is a concern, large diameter column shafts are preferred over pile groups. This eliminates the need for deep excavation and shoring to place the pile cap below the scour depth.
- Cast-In-Steel-Shell (CISS) piles are limited in many cases because of environmental constraints such as limited vibrations and noise levels.

2.3.3.2 Utah Department of Transportation (UDOT)

Bridge foundations for projects typically consist of deep foundations (piles or drilled shafts) or spread footings. Spread footings are generally not considered acceptable at stream crossings. This agency conducted an economic analysis to determine the optimal foundation system among the technically feasible ones (UDOT 2014).

The foundation policy does not allow the use of auger-cast piles, timber piles, rammed piers, or stone columns as a substitute for deep foundations to support the bridges. The applicable foundation types for a bridge project are selected based on anticipated loads and scour depths (where applicable), along with proper consideration of settlements, downdrag, bearing resistance, lateral load resistance, seismic hazards, constructability, and other applicable factors. The foundation policy allows 6 in. of construction tolerance in the pile or drilled shaft details. Contractor pay reductions apply to piles offset 6 in. or greater from the design location, and piles are rejected if offset is 12 in. or greater from the design location.

The foundation policy specifies that driven piles shall consist of steel H-piles, steel pipe piles (typically concrete-filled), or prestressed concrete piles. Yield strength values used in the design of these piles shall not exceed the values prescribed in the specification ASTM A-252 Grade 2 (35 ksi) or Grade 3 (45 ksi) steel for Pipe Piles, and ASTM A-36 or A-50 steel for H-piles.

UDOT standard specification 02466 is intended for use with shafts of relatively small diameter and depth. Where necessary, special provisions are developed for drilled shaft construction to addresses specific construction issues relevant to the project. The policy specifies that for the foundation design with pile support (driven or drilled CIP shafts), the following shall be considered:

- The method of support (skin friction and/or end bearing) in clays and dense sandy materials
- Suitable pile type(s) – reasons for choice and/or exclusion of types
- Pile toe elevations and length of piles
- Pile axial compression resistance at the applicable AASHTO LRFD limit states
- Reduction of pile resistance due to negative skin friction
- Scour depth (elevation) if applicable and method of determination
- Effects of induced loads on piles due to adjoining new or existing embankments.

For the foundation design with footing support, the following shall be considered:

- Bottom elevation of the footing
- LRFD bearing resistance
- Approximate settlements at loads corresponding to the applicable AASHTO LRFD limit states
- Brief description of material on which the footing is to be placed and soil improvement, if expected
- Scour depth.

2.3.3.3 Iowa Department of Transportation (Iowa DOT)

The office of Bridges and Structures generally selects among three types: piles, drilled shafts, and spread footings. This is because most Iowa bridge sites are in rural areas (Iowa DOT 2003; Iowa DOT 2014).

Usually, the site conditions and economy favors using piles because the bedrock is seldom near the surface. However, in cases where pile driving would disturb adjacent structures, drilled shafts may be considered. In cases where bedrock is close to the planned bottom elevation of a substructure component, spread footing shall be used by notching into the bedrock (Iowa DOT 2014). The Soils Design Section recommends a foundation type with one of the following:

- Point-bearing piles driven to a rock formation
- Friction or friction plus bearing piles driven to a specified load capacity, below any expected scour elevation
- Drilled shafts
- Spread footings founded directly on a rock formation.

The foundation policy specifies that the engineer should investigate slope stability issues and settlement issues to provide foundation recommendations or discussions. At least one boring per foundation must be tested by using standard penetration methods so that 1994 Foundation Soils Information Charts may be used to check the foundation type and design. The following factors shall be considered when selecting a pile type:

- Displacement piles may not be drivable in materials with N-values greater than 25.
- Displacement piles may not be drivable if identifiable boulder layers are present.
- Displacement piles may not be drivable through dry sands.
- Steel H-piles with driving shoes may be required if inclined bedrock surfaces are to be penetrated.
- Steel H-piles with driving shoes may be required if significant layers of N>100 are to be penetrated.

2.3.3.4 North Carolina Department of Transportation (NCDOT)

Policy does not allow timber piles for any structure foundation, nor does it allow spread footings in locations with scour potential. Also, the design of bridges with Mechanically Stabilized Earth (MSE) walls as structural foundations is not permitted (NCDOT 2014a, b).

For driven piles, testing shall consist of Pile Driving Analyzer (PDA) with Case Pile Wave Analysis Program (CAPWAP) or static load testing. A minimum of one PDA or Static Load Test is required per combination of pile size, pile type, and pile driving hammer at each bridge site using driven piles. For drilled shafts, testing shall consist of Crosshole Sonic Logging (CSL) testing or an alternative testing procedure approved by NCDOT. For shallow foundations, such as spread footings, testing shall consist of plate load testing or full scale load tests (NCDOT 2013).

The LRFD Driven Pile Foundation Design Policy of NCDOT specifies using (1) Prestressed concrete piles, (2) Steel H-piles, and (3) Steel pipe piles. The pile type is selected based on drivability analysis, pile driving stress limit, and scour resistance and downdrag load. The foundation recommendations for a project include: (1) Required factored resistance, (2) Required driving resistance, (3) Estimated pile lengths and minimum tip elevation, (4) Final point of fixity, (5) Hammer energy, and (6) Scour critical elevation (NCDOT 2014b).

2.3.3.5 Maryland State Highway Administration (MDSHA)

Policy indicates foundation piles may be either batter piles that are driven at an angle or plumb piles that are driven straight down. Driving piles alongside previously driven piles will frequently cause those piles already in place to heave upward. Heaved piles should be re-driven to firm bearing. Test piles shall be driven to determine the length of pile required for permanent foundation. In addition, standards include the following pile types for deep foundations (MDSHA 2002; MDSHA 2014):

1. Steel H-pile (10 in., 12 in., and 14 in.)
2. Cast-in-place concrete pile with a steel shell.

For bridge construction, the generally used type of displacement pile is the Open End Steel Pipe Pile. After driving to the final position, this pile is filled with concrete only when specified (MDSHA 2014).

2.3.3.6 Oregon Department of Transportation (ODOT)

The common foundation types are: (1) Spread footings, (2) Piles, and (3) Drilled shafts. Exploratory holes are drilled near the proposed pile locations to investigate the subsurface materials. Oregon DOT (2010) specifies referring to the FHWA manual, *Design and Construction of Driven Pile Foundations* (FHWA-HI-97-013, 1996), for the design of pile foundations and other pertinent information.

The common driven pile is the steel pipe pile. This is because, in most cases, the substructure conditions are considered unsuitable for an end-bearing pile design. Both open-ended and closed-ended steel pipe piles are used. In most cases, the open-ended steel pipe piles are filled with concrete. Oregon DOT's 1995 foundation report considers closed-ended steel pipe piles (displacement piles) as the most appropriate pile type for bridge sites in Klamath Falls area (Oregon DOT 2005).

Standard prestressed concrete piles are rarely used due to the following reasons (Oregon DOT 2005):

- They typically have less bending capacity than steel piles for a given size.
- They are difficult to connect to the pile cap for uplift resistance.
- They are inadequately reinforced for plastic hinge formation.
- They present difficulty in handling, pile driving, and splicing.
- They are typically more expensive than steel for a given capacity.

2.3.4 Foundation Construction

Foundation construction while the existing facilities in service or under highly constraint conditions are reviewed. Section 2.3.4.1 documents foundation construction while the existing bridge is in service. Section 2.3.4.2 documents other case studies. The information documented in these two sections is used in Chapter 4 for developing guidelines and recommendations for foundation construction while the existing bridge is in service.

2.3.4.1 Foundation Construction While the Existing Bridge is in Service

Several projects listed in Table 2-1 had the foundations constructed while the existing bridge was in service. These projects are reviewed, and the pertinent information was documented. The specific information documented includes a description of the exiting bridge and the site, existing bridge foundation type, constraints, alternatives considered, and the foundation solutions. The 4500 South (SR-266) over I-215 project in Salt Lake City, Utah, is an example for a bridge project where the foundations and the substructure was constructed while the existing bridge was in service. As an example, this project information is presented in Table 2-10. Using a similar format, the rest of the project information was documented and presented in Appendix A.

Table 2-10. Foundation Solutions: 4500 South (SR-266) over I-215 Project

Bridge Configuration
Four-span 244-ft-long and 77.2-ft-wide bridge was replaced with a 172-ft long and 82-ft wide single-span bridge (Figure 2-18).
Existing Foundation Type
• Abutments are labeled as #1 and #2 (Figure 2-18). • Abutment #1 was on spread footing while #2 was on piles. • All three piers were supported on spread footing.
Constraints
• Maintaining traffic on the bridge during substructure construction (two abutments) • The bridge is in a steep grade (11.89%); hence, headroom at one of the abutments is limited.
Alternatives Considered for the Site
Information not available
Solution
• Each new abutment was constructed in front of the existing abutment, and required excavating in front of the existing abutments (Figure 2-19 and Figure 2-20). • Temporary soil nail walls were constructed to retain the slopes in front of the existing abutments (Figure 2-20 and Figure 2-21). • Micropiles were used to enhance the stability of abutment #1 on spread footing (Figure 2-19).

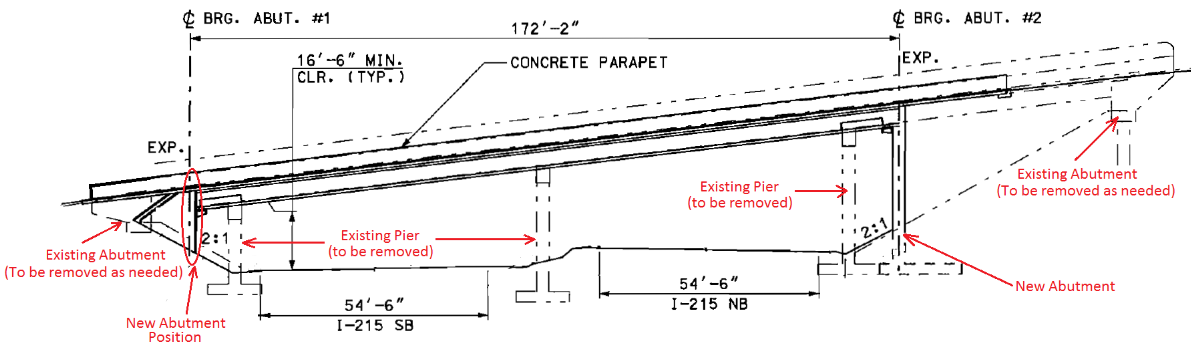


Figure 2-18. 4500 South (SR-266) over I-215 bridge elevation view

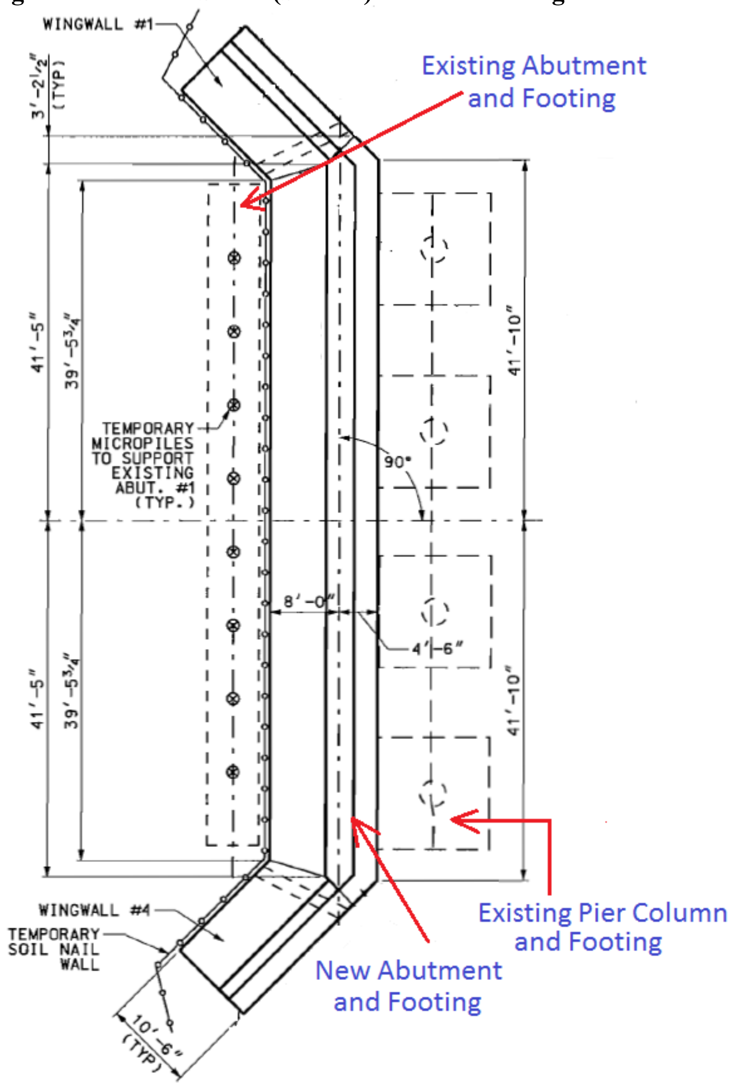


Figure 2-19. Layout of new abutment # 1

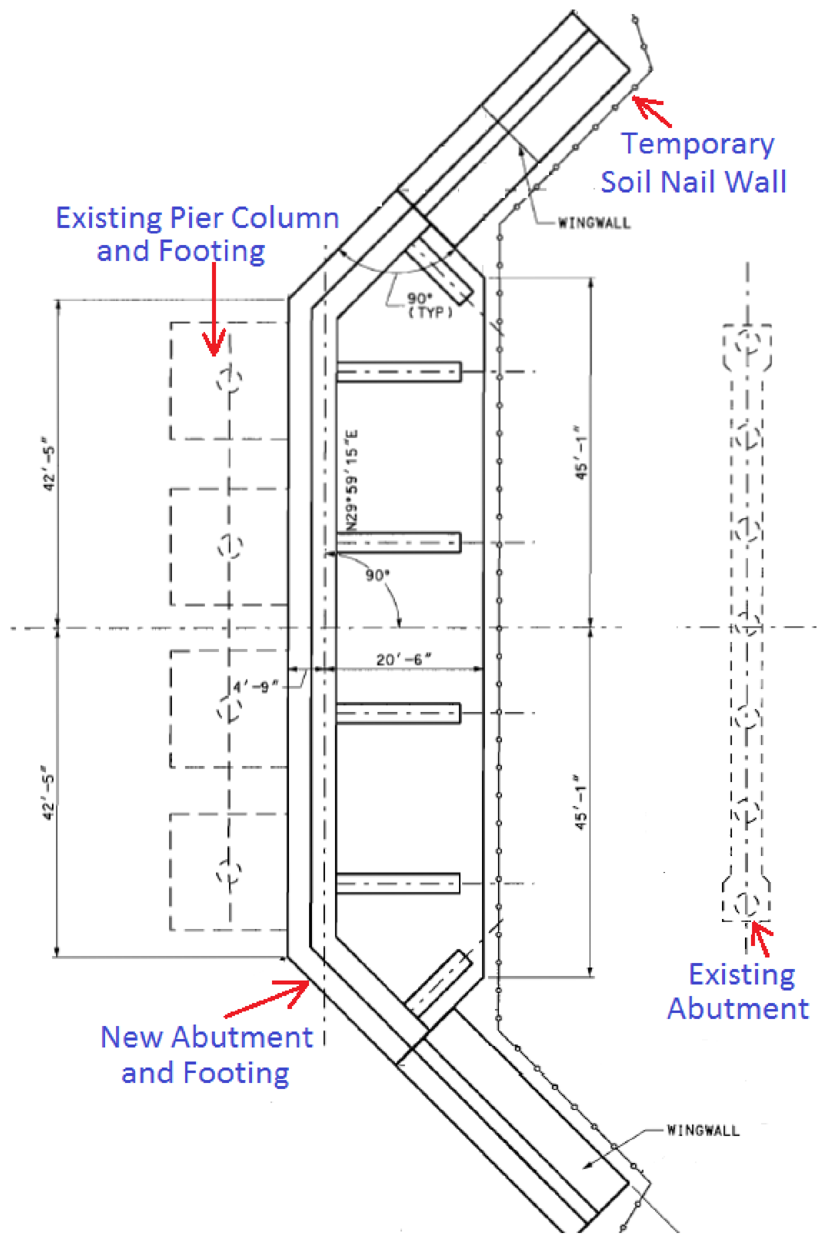


Figure 2-20. Layout of new abutment # 2

Figure 2-21. New abutment #1 construction (Photo courtesy: UDOT)

2.3.4.2 Foundation Construction Case-Studies

The foundation capacity enhancement or retrofit work performed for other structural systems are described. Typical information documented from such projects include the following: problem description, existing foundation type, constraints, alternatives considered, solution, justifications for selecting a specific foundation or construction method, and remarks on the project. While one such example is presented in this section, the rest of the case studies are documented using a similar format, and they are presented in Appendix A. The example presented in this section is the expansion of the House of Representatives Building in Lansing, Michigan (Rabeler et al. 2000).

Table 2-11. House of Representatives Building Expansion in Lansing, Michigan (Rabeler et al. 2000)

Problem Description

- To provide additional office spaces, it was decided to construct 9 additional floors on top of the five-story west end of the Board and Water Light (BWL) building in Lansing, Michigan.
- While some of the existing columns were strengthened, new columns were extended through the existing building all the way down to the basement, which was used for parking, offices, and storing mechanical equipment.

Existing Foundation Type

- Information not provided.

Constraints

- Construction of new foundations at the basement level
- Uninterrupted regular functioning of the building with the original tenants
- Low headroom (7.90 ft to 9.85 ft)
- Limited pile cap dimensions at several locations for the new piles (limited by hallway width of 3.30 ft)
- Heavy loads on the new foundations (ranging from 1,000 kips to 2,000 kips)

Alternatives Considered for the Site

- Low headroom drilled piers (caissons)
- Drilled cast-in-place (D-CIP) micro-piles

Solution

- High capacity, 9 in. diameter, D-CIP micro-piles with a single threaded steel bar was used (see Figure 2-22 for details.) Also, a 5 ft long permanent steel casing was included at the top to enhance the lateral load capacity.
- No. 18 or No. 20, Grade 75, continuously threaded DYWIDAG bars were used as pile core steel. Rebar size was selected based on the load capacity demand.
- Steel bars were cut into a nominal length of 7.9 ft to handle within the limited space.
- DYWIDAG couplers were used to connect the bars, and PVC centralizers (Figure 2-23) were used to position the reinforcing bar in the borehole.
- A neat cement grout mix was specified with Type II cement, water, and an admixture to increase workability with lower w/c ratio.
- Construction activities and pile installation were scheduled not to disturb the newly placed piles at a distance +/- 3 ft within a pile cap. Basically, the work on adjacent piles was not started until the grout had a chance to cure overnight.
- Individual pile capacities ranged from 150 kip to 190 kip.
- Overall pile lengths ranged from 32 ft to 54 ft.
- A small diesel powered hydraulic-tracked drill that can pass through a 2.7 ft doorway was used.

Justification

- Bids for low headroom drilled piers (caissons) were expensive and determined to be cost prohibitive.
- Shallow depth to dense clay till (20 ft) and weathered sandstone (30 ft) from the ground surface made it possible to design high capacity D-CIP micro-piles.
- High capacity of the D-CIP micro-piles reduced the number of piles and the pile cap dimensions to address the space constraint for pile cap size.

Remarks

- Specialty contractor, Spencer White and Prentis (SWP)
- Work was scheduled during off-hours so as not to interfere with the building operation.
- The pile production ranged from 1 to 2 piles completed per 8-hour working shift.

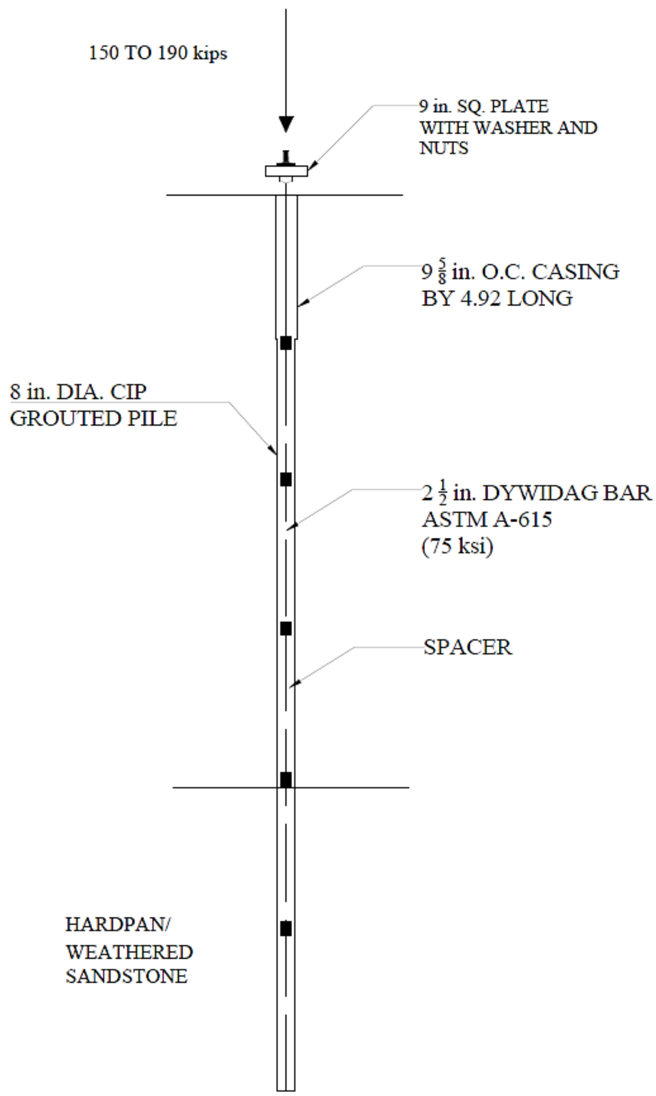


Figure 2-22. Micropile profile

Figure 2-23. PVC centralizer (Source: DSI 2015)

2.3.4.3 Summary

The data compiled from the review of past projects are analyzed and summarized below:

- Shallow foundations, drilled shafts, driven piles (closed-ended pipe piles with conical reinforce tips and H-piles), and micropiles were used to construct foundations while the existing bridge was in service.
- Typically, cast-in-place concrete columns, walls, and caps were used to build the substructure under the existing bridge while in service.
- Adequate headroom was maintained by locating new deep foundations in between the girders.
- Batter micropiles were used to enhance the lateral load capacity.
- Micropiles were used to enhance the stability of a shallow foundation while the construction was performed underneath the bridge.
- Soil nail walls were commonly used to stabilize the slopes: consequently, the existing bridge.
- Existing abutments, when located behind the new abutments were left in place. After the new foundation and substructure construction were completed and the existing bridge was demolished, these abutments were partially demolished to complete the necessary construction activities. Similar practices were documented for bents and piers; they were demolished partly without removing the entire structure.
- Outrigger bents and deep foundations were used to build the substructure when the new structure was wider than the existing bridge. When the deep foundations are located outside the existing bridge footprint, lateral loads control the foundation and substructure design. This requires adequate embedment of the foundation and a larger cross section. Hence, drilled shafts were commonly used.
- Driven piles were used to support the grade beam, which was used for sliding approach slabs with the new superstructure. After completing the slide, the grade beam was left in place as the permanent support of the approach slab.
- Driven piles were installed between the abutment and the pavement by using temporary lane closures. In that case, precast panels were used as a temporary pavement.

- Driven piles were installed through holes made in the bridge deck while maintaining traffic on the bridge using temporary lane closure.
- In confined spaces, mostly micorpiles are used. However, drilled shafts were installed with 5 ft headroom to retrofit existing foundations of a building.
- Compaction grouting and jet grouting are used for retrofit.
- Pile installation impact on the soil confining pressure around existing foundation need to be considered for stability of existing structures.

2.4 COST BENEFIT ANALYSIS

The construction cost of an ABC project is usually higher and ranges between 6% and 21% over the cost estimate of traditional construction (FHWA 2011). Complexity, risk, and time constraints are the three main factors that contribute to the increase in ABC construction cost. ABC is new and the bridge community is gaining experience through limited implementations as demonstration projects. The strict time constraints will always be a part of ABC projects in order to reduce the mobility impact time. These time constraints require innovative methodologies such as SPMT move and SIBC to be deployed, and additional work before on-site construction; thus leading to additional costs. ABC provides several benefits to the agency and users (FHWA 2013b). At present, emphasis is to standardize design, detailing, equipment, and construction process as well as employing local contractors to deliver the projects. Once the ABC project delivery methods become the common practice, cost is expected to be comparable or lower than the conventional construction cost (UDOT 2008).

In order to perform cost-benefit analyses for each project delivery alternative, parameters specific to each alternative need to be identified. The data and other information collected from the projects listed in Table 2-1 and the MDOT report RC-1602 by Aktan and Attanayake (2013) were analyzed to develop a list of cost and benefit parameters. Further, the cost calculation models were developed and calibrated using the data from the projects listed in Table 2-1. A detailed description of the cost and benefit parameters, cost estimation models, and the process for cost-benefit analysis is presented in Chapter 5.

2.5 BRIDGE SLIDING MECHANISMS AND PARAMETERS

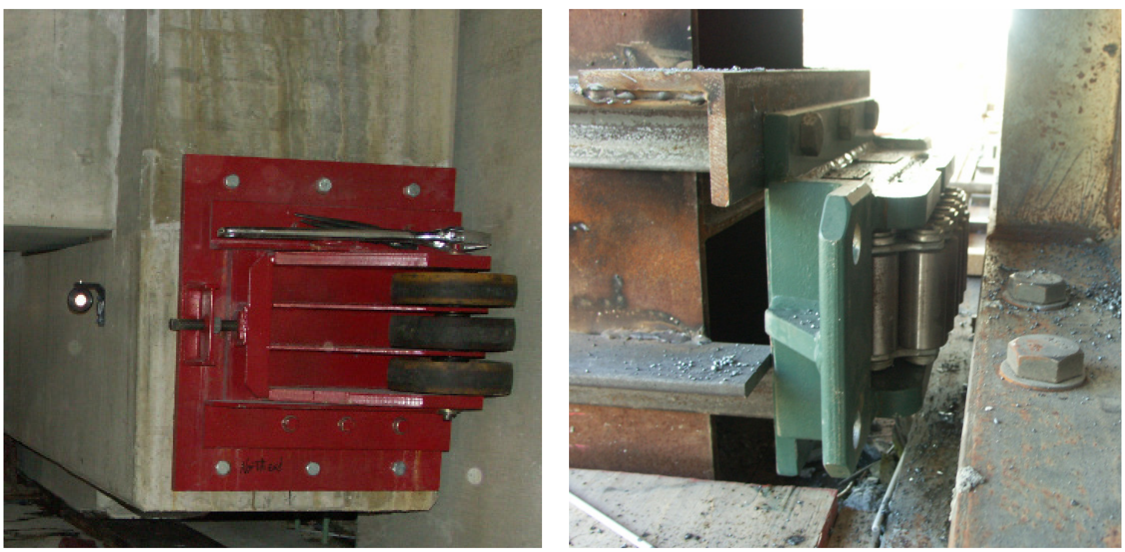
2.5.1 Sliding Mechanisms

The sliding mechanisms that can be used for sliding a bridge as well as maintaining its alignment are reviewed. Selection of the appropriate mechanism depends on design of the slide system (i.e., push or pull, railing girder, sliding girder, etc.), bridge geometry, weight, tolerances, and contractor experience and preference.

2.5.1.1 Industrial Rollers

Industrial rollers such as the ones manufactured by Hillman, are typically placed inside the tracks under the girders or the end diaphragms to support gravity loads while allowing the bridge to be moved onto the permanent substructure (Figure 2-24). The rollers are placed inside the tracks to limit movement to the direction of sliding. Any adjustments to the bridge in the direction perpendicular to the slide direction, is a challenge. Precise track alignment is essential to prevent binding or jamming of the rollers. Industrial rollers (Figure 2-25a) and the ones manufactured by Hillman (Figure 2-25b), are also used to keep the bridge aligned when the structure is slid over PTFE pads (commonly known as Teflon). The characteristics and properties of PTFE pads are discussed in the next section. FHWA (2013c) lists several advantages and challenges of industrial rollers as the primary mechanism to move a bridge. Also included are a few suggestions to improve the challenges. Industrial rollers have a lower static and dynamic friction than PTFE pads. The lower friction allows using lower capacity hydraulic systems. However, lower friction requires a mechanism to hold the structure in place as well as a mechanism to break the motion, if needed. Additional concerns regarding the use of rollers as the sliding mechanism include the large concentrated loads transferred through the rollers, maintaining a clean and clear travel path, and maintaining a smooth transition between the temporary and the permanent substructures.

Figure 2-24. Industrial rollers placed under the end diaphragm (Source: FHWA 2013c)



(a) Industrial rollers (b) Hillman rollers

Figure 2-25. Rollers used for maintaining alignment

2.5.1.2 PTFE Pads

Polytetrafluoroethylene (PTFE) pads are used as sliding surfaces for the stainless steel shoes attached to the sliding structure (Figure 2-26). Friction between PTFE and stainless steel shoes can be reduced with lubricants. Typical static and dynamic friction values are presented in Section 2.5.2.3. A commonly available lubricant in lieu of synthetic types is dish soap (Shutt 2013b). When a bridge is slid onto place using PTFE pads, the direction of movement is not constrained with the pad orientation. This flexibility allows steering the bridge into its final position. However, the bridge can easily drift laterally when unequal forces are applied, an alignment difference between the railing girders exists, or a combination thereof. Hence, the use of PTFE pads requires guides or rollers attached to the sides as lateral restraints to control bridge alignment (Figure 2-25). Several challenges encountered during recent projects implemented in Michigan, and the remedial measures used by the contractors are discussed in Section 6.3.

Figure 2-26. Steel reinforced elastomeric pads with PTFE layers

Linear bearings can also be used for the sliding mechanism in bridge sliding. Linear bearings are similar to rollers designed to slide only in one designated direction. Linear bearings can be sealed and include impregnated lubricant for reduced friction coefficient. Impregnated lubricant is contained and will not spill.

2.5.2 Slide Operation Parameters

A structure can be moved by prescribing a displacement (displacement control) or a force that ramps up to a value greater than the resisting forces developed in the system (force control). Sections 2.5.2.1 and 2.5.2.2 describe the displacement control and force control methodologies, along with the variation of acceleration, velocity, and displacement against time when such methodologies are implemented.

Friction at the sliding surface is an important parameter in SIBC move operations. Bridges are slid over sliding mechanisms such as Hillman rollers and stainless steel over PTFE pads. Static and dynamic friction coefficients are used to calculate the required pull or push forces to slide a bridge as well as to design temporary and permanent substructure. The friction coefficient is the ratio between horizontal force and the normal force. Identifying and evaluating the parameters that affect static and dynamic friction coefficients and the decay rate from static to dynamic friction is important to properly design a slide system. The dynamic friction is also known as kinetic or sliding friction. To be consistent with the literature, the term *kinetic friction* is used throughout this document. A thorough literature review on PTFE-steel interface friction as well as the parameters affecting the friction was performed and documented in Section 2.5.2.3.

2.5.2.1 Displacement Control

As per the displacement control methodology, a structure is expected to move a distance equal to the prescribed magnitude and towards a specified direction. Under the controlled displacement, the movement of the structure is independent of the sliding resistance with sufficient hydraulic capacity. When a bridge is slid under the displacement control, the bridge will move along a prescribed alignment irrespective of the friction forces developed at the sliding surfaces. Upon initiating the move under displacement control, the structure is subjected to an initial acceleration that is proportional to the rate of change of velocity or the second derivative of displacement with respect to time. By ramping the displacement target, the bridge can be pulled or pushed with a small initial acceleration to minimize the inertia forces developed in the system. Figure 2-27 shows the variation of acceleration, velocity, and displacement against time. Implementing only the displacement control methodology may be problematic because the objective is to achieve the prescribed displacement irrespective of the forces developed in the system. Binding of rollers or pads may cause undesirable forces developed in the system under displacement control. Hence, the applied force also needs to be monitored, and limits need to be prescribed. The hydraulics need to be shutoff when the forces exceed the limit. As shown in Figure 2-27, after the initial period, the structure can be slid into place at a constant velocity provided the hydraulic system is capable of consistently moving the bridge without jamming or binding of the pads or rollers.

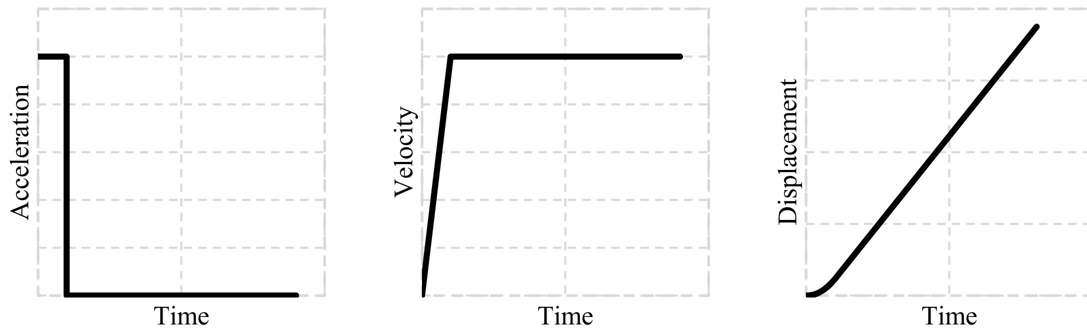


Figure 2-27. Acceleration, velocity, and displacement variation against time in a displacement control system

2.5.2.2 Force Control

In force control methodology, a force is gradually applied until a predefined limit is reached. In the case of SIBC, the force is gradually applied to the superstructure until the sliding resistance is overcome and the structure motion starts. At this point, the force should be maintained at a constant value allowing the structure to gain some acceleration until it reaches a certain velocity that is sufficiently high to reduce static friction and reach kinetic friction.

Figure 2-28 shows the applied force and resistance force variation against time in a force control system. As shown in the figure, the force is gradually increased. Even after the system starts moving, the force continues increasing. As shown in Figure 2-29, when the applied force reaches a specific value that is larger than the resistance, the superstructure starts to accelerate. As the sliding velocity increases, the sliding resistance decreases. The net force, which is accelerating the superstructure, is increased due to decreasing resistance. With increasing velocity, friction becomes kinetic and the net force becomes constant. As a result, acceleration becomes constant. Beyond that time, the velocity increases linearly under constant acceleration. With a linearly increasing velocity, the displacement increases quadratically.

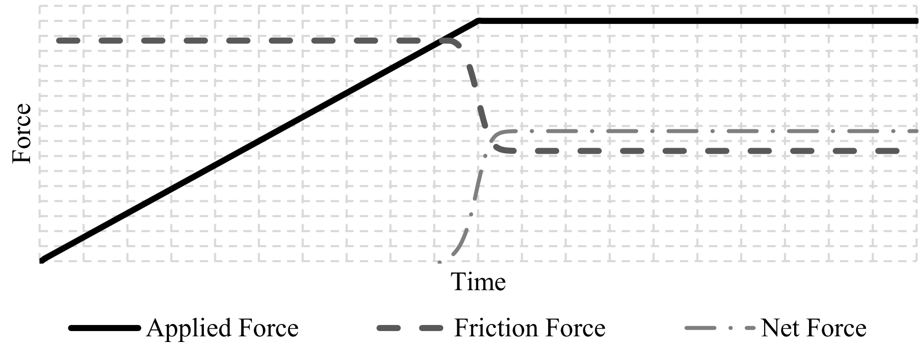


Figure 2-28. Applied force, friction force, and net force variation in a force control system

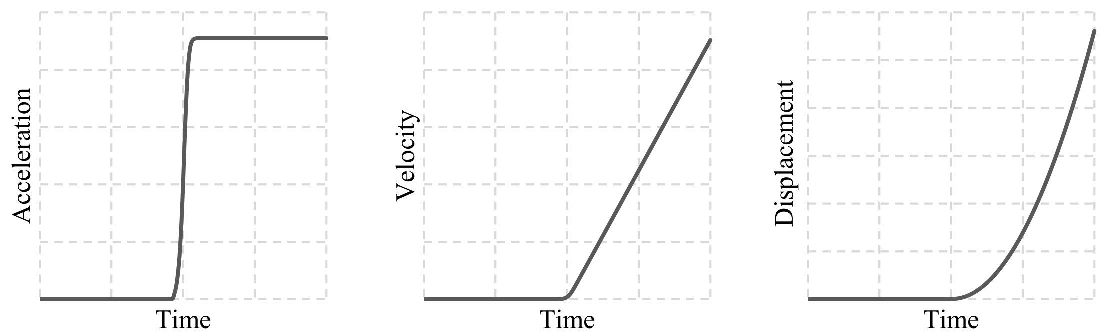


Figure 2-29. Acceleration, velocity, and displacement variation against time in a force control system

2.5.2.3 Sliding Friction

According to the classical isotropic Coulomb friction model given in Eq. 2-1, the friction at a given time can be calculated knowing static and kinetic friction coefficients as well as the exponential decay rate (Oden and Martins 1985).

$$\mu = \mu_k + (\mu_s - \mu_k)e^{-d_c \dot{\gamma}_{eq}} \quad (2\text{-}1)$$

where: μ_k is the kinetic friction coefficient, μ_s is the static friction coefficient, d_c is a user defined decay coefficient, and γ_{eq} is the slip rate.

The friction model defined in Eq. 2-1 requires defining static and kinetic friction coefficients and a decay rate. The literature review is limited to the friction between PTFE-steel interfaces; hence, this section documents the static and kinematic friction values as well as the factors affecting the interface friction.

According to Hwang et al. (1990), the parameters that affect PTFE-steel interface friction are sliding velocity, normal pressure, PTFE composition, steel sliding surface roughness, surface treatment (lubricant applied at the interface), temperature, and the angle between the surface polishing of steel and sliding direction. AASHTO (2014) Table 14.7.2.5-1 provides kinetic friction coefficients for various PTFE-stainless steel interfaces (Figure 2-30). Friction coefficients given in AASHTO (2014) are for service conditions. The sliding velocity of a superstructure in a move operation is extremely slow, and it might emulate quasi-static conditions.

According to AASHTO (2014), kinetic friction decreases with an increase in normal pressure and use of lubrication. Bondonet and Filiatrault (1997) conducted a series of experiments to evaluate the friction coefficient at the PTFE-steel interface. The experiments were conducted at different bearing pressures and sliding frequencies to simulate earthquake load effects. The friction coefficient recorded at the first peak of the first loading cycle represents the static value. After the motion starts and the resistance becomes contant, steady state friction is recorded and considered as the sliding friction coefficient. Figure 2-31 shows the variation of the static and kinetic friction coefficients at PTFE-steel interface with respect to the normal pressure and the sliding velocity. According to the results shown in Figure 2-31, friction is reduced with an increase in normal pressure as well as with a decrease in sliding velocity.

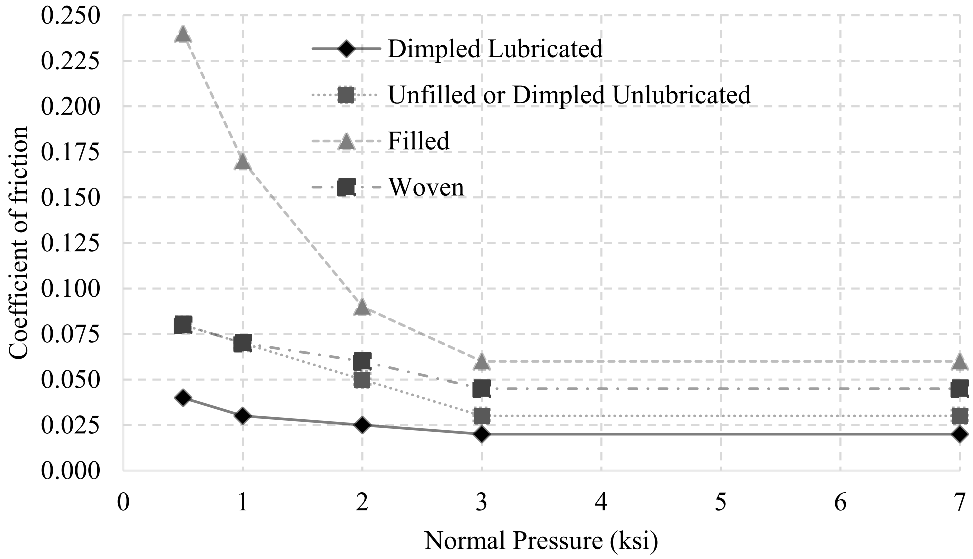


Figure 2-30. Design coefficient of friction with steel surface roughness (SR) of 8 μ-in (Source: AASHTO 2014)

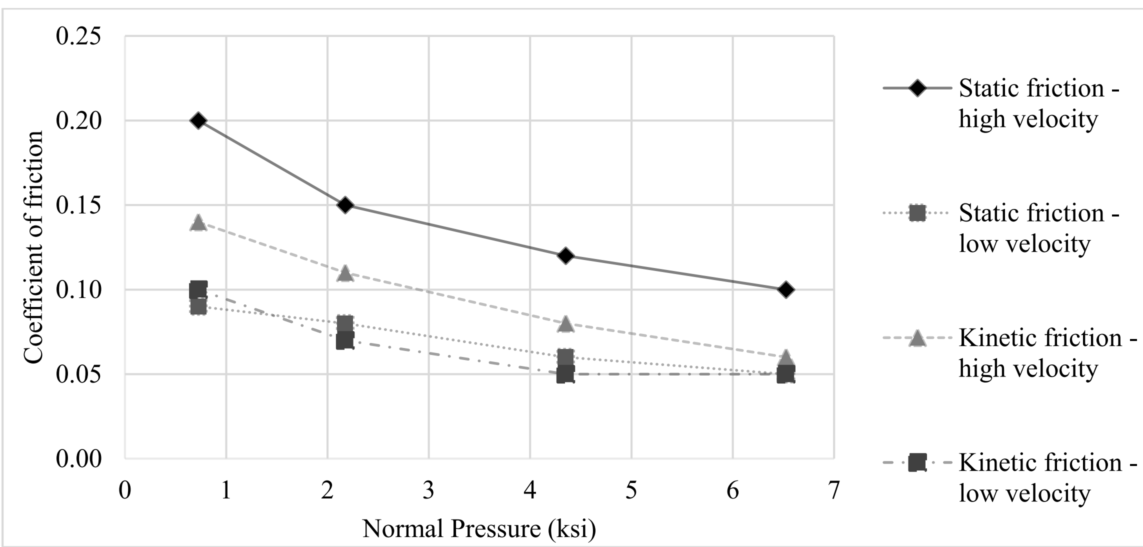


Figure 2-31. Friction coefficient at the PTFE-steel interface (Source: Bondonet and Filiatrault 1997)

Figure 2-32 shows the variation of friction with pressure and velocity when the surface roughness of steel is two. According to the data shown in Figure 2-32, the coefficient of friction reduces with the pressure at the interface. Under constant surface roughness, the impact of sliding velocity on the friction coefficient variation is inconclusive. Figure 2-33 shows the coefficient of friction variation with pressure, velocity and, surface roughness. As shown in the figure, increase in surface roughness increases the friction. According to Figure 2-33, changing surface roughness from 2 to 7 increases the friction coefficient by 0.05 at a sliding velocity of 0.1 in/sec. At a sliding velocity of 0.009 in/sec and a surface roughness increase from 2 to 10, the friction coefficient is increased by 0.015. Hence, higher velocities have a greater impact on the change in friction coefficient with changing surface roughhess. According to Constantinou (1994), an increase in normal pressure reduces the kinetic friction coefficient, and the rate of reduction depends on the velocity (i.e., increase in velocity results in a higher rate of reduction in the coefficient of friction.) According to Figure 2-33, with 0.009 in/sec velocity and a surface roughness of 10, the friction coefficient is less than 0.06. Comparing this result with AASHTO (2014) for an unfilled or dimpled unlubricated PTFE friction coefficient, under slow sliding speed, the the friction coefficient remains below 0.075.

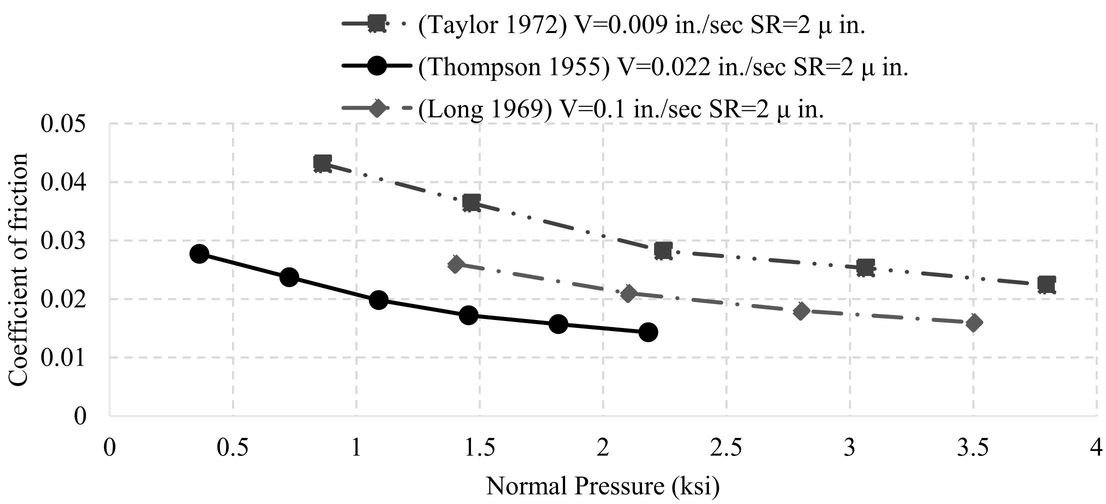


Figure 2-32. Variation of PTFE-steel interface friction with steel surface roughness (SR) of 2 μ in., velocity (V), and pressure (Source: Hwang et al. 1990)

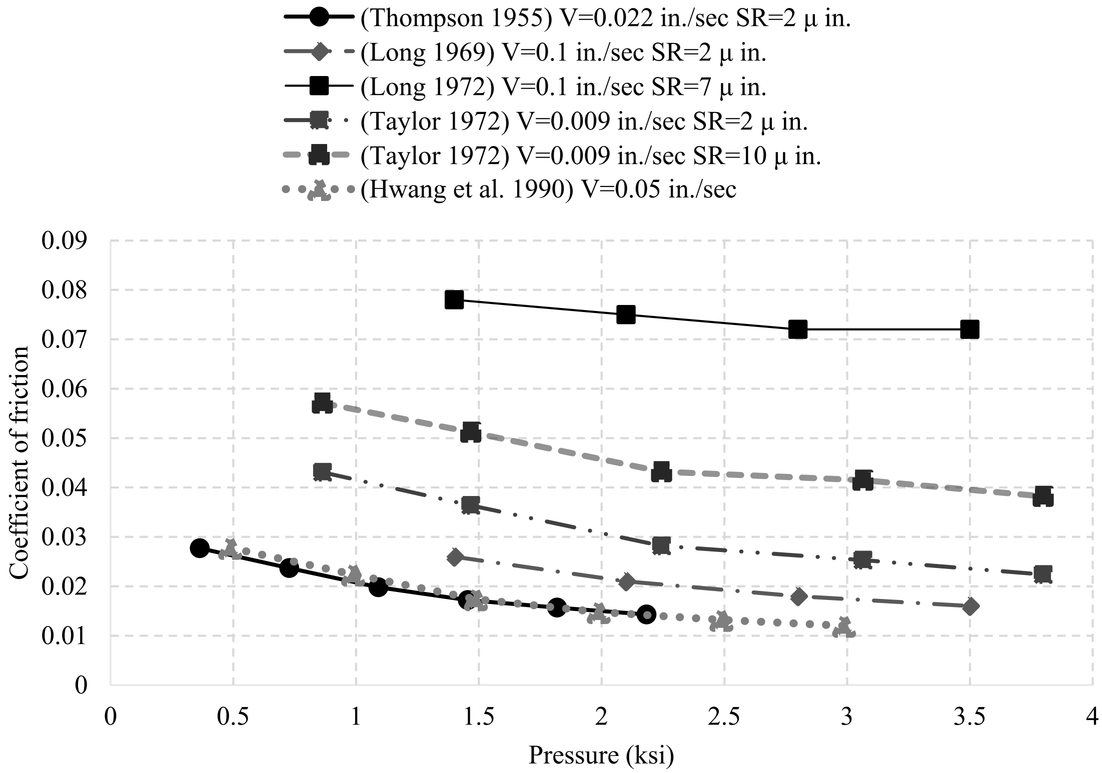


Figure 2-33. Variation of PTFE-steel interface friction with pressure, sliding velocity (V), and surface roughness of steel (SR) (Source: Hwang et al 1990).

In addition to the experimental results shown above, Table 2-12 presents static and kinetic friction values documented in the literature. Unfortunately, references did not explicitly document the type of PTFE and the conditions under which the data was recorded. Kinetic friction coefficients given in SHRP2 R04 (2015) and MDOT (2014c) are comparable to the AASHTO (2014) for dimpled lubricated PTFE friction values when the PTFE pads are under less than 1 ksi normal pressure. As shown in Figure 2-31, the static friction efficient is less than 0.1 (or 10%) under low sliding velocity and a normal pressure of under 1 ksi. Considering the data presented in Figure 2-31, FHWA (2013c), SHRP 2 R04 (2015), and MDOT (2014c), the use of 10% static friction is reasonable for sliding force calculation.

Table 2-12. Static and Kinetic Friction Values

Source	Static and Kinetic Friction Coefficients
DuPond (1996)	Static friction coefficient: 5-8% (at normal pressure = 0.5 ksi) Kinetic friction coefficient = 3% (at normal pressure = 0.3 ksi)
Blau (2009)	Static friction coefficient = 4% (for fixed PTFE and moving steel surface)
UDOT (2013)	Static friction coefficient = 5-15% (according to initial loading conditions) Kinetic friction coefficient = 1 -2%.
SHRP 2 R04 (2015)	Static friction coefficient = 9-12% Kinetic friction coefficient = 5-6% (for the lubricated PTFE surface)
MDOT (2014c)	Static friction coefficient = 10%. Kinetic friction coefficient = 5%. (Pressure is 0.435 ksi)

2.6 TEMPORARY STRUCTURES

A need for new temporary structures has emerged with the implementation of ABC methods such as SIBC and SPMT moves. In the case of SIBC, a temporary structure is built adjacent and connects to the existing bridge. The new bridge superstructure is fabricated on top of the temporary structure, which is expected to provide vertical support for the new superstructure and guide it to the permanent position. The design need for temporary structures for SIBC and SMPT projects is new. To provide some clarity to the design process characteristics of the temporary structures, several SIBC projects were reviewed and presented in Section 2.6.1. Generally, in SIBC projects, the contractor is responsible for the design of the temporary structure. In most instances, the contractor is required to submit design calculations for the temporary structure to be reviewed and approved by the highway agency overseeing the project. However, these design calculations may not be easy to review because of different specifications or guidelines used during the design process. In addition to documenting site and temporary structure characteristics, specifications and guides for temporary structure design are documented under each project selected for this review. Later, Section 2.6.2 presents an overview of the specifications and guidelines specific to SIBC implementations.

2.6.1 Slide-In Bridge Construction Implementations – Site and Temporary Structure Characteristics

Twenty-nine SIBC projects were reviewed. However, twenty-one projects were excluded from the review when (1) the new bridge superstructure was longitudinally launched, (2) the new bridge superstructure includes more than 3-spans, (3) the temporary structure is reinforced concrete, (4) the temporary steel structure is a unique design due to special site conditions, or (5) there exists lack of project information to obtain an adequate site description. Therefore, the eight projects listed in Table 2-13 were analyzed in detail. As an example of the format describing the site and temporary structure characteristics, Massena Bridge in Iowa is included in the subsection below. The information on the remaining seven projects is presented in Appendix B.

Table 2-13. List of SIBC Projects Selected for a Detailed Review

State	Project Name	Year	Slide-in Technique	
			Push or Pull	Slide or Roll
Iowa	Massena Bridge	2013	*Pull*	*Roll*
Michigan	M-50 over I-96	2014	Push	Slide
Michigan	US-131 over 3 Mile Road	2014	*Pull*	Slide
Minnesota	Larpenteur Ave Bridge	2014	Push	Slide
Nevada	West Mesquite Interchange at 1-15	2012	Push	Slide
Utah	I-80 at Summit Park	2011	Push	Slide
Utah	I-80 at Wanship	2012	*Pull*	Slide
Utah	I-80 over 2300 East	2009	Push	Slide

Specific terms that are repeatedly used throughout this section to describe project sites, bridge superstructures, and temporary structures are defined below:

(1) Extended Piles –The driven piles as pile bents of the temporary structure that extend above the ground level.

(2) Longitudinal Grade – The grade of the roadway along the path that vehicles travel.

(3) Profile Grade - Refers to a cross-section, which shows the roadway grade with respect to the roadway crown.

(4) Superelevation – The titling of the roadway cross section in one direction to help offset centripetal forces developed as the vehicle goes around a curve.

2.6.1.1 Massena Bridge – Iowa

2.6.1.1.1 Site Characteristics

The new 2-lane bridge carries IA-92 eastbound and westbound traffic over a 14 ft wide stream. The profile grade along the replaced bridge consists of mirrored downgrades of 2.0% from the roadway crown, that transition into 1:6 downgrades on the embankments. The stream below the bridge that flows from north to south with a longitudinal grade of 3.2% has parallel banks with profile grades of 2.5%.

2.6.1.1.2 Superstructure

Length and width of the new single-span, prestressed concrete girder superstructure is 124 ft and 47 ft 2 in., respectively. The change in the longitudinal grade of the bridge superstructure was insignificant. The maximum vertical clearance between the superstructure and stream was 22.5 ft.

2.6.1.1.3 Temporary Structure

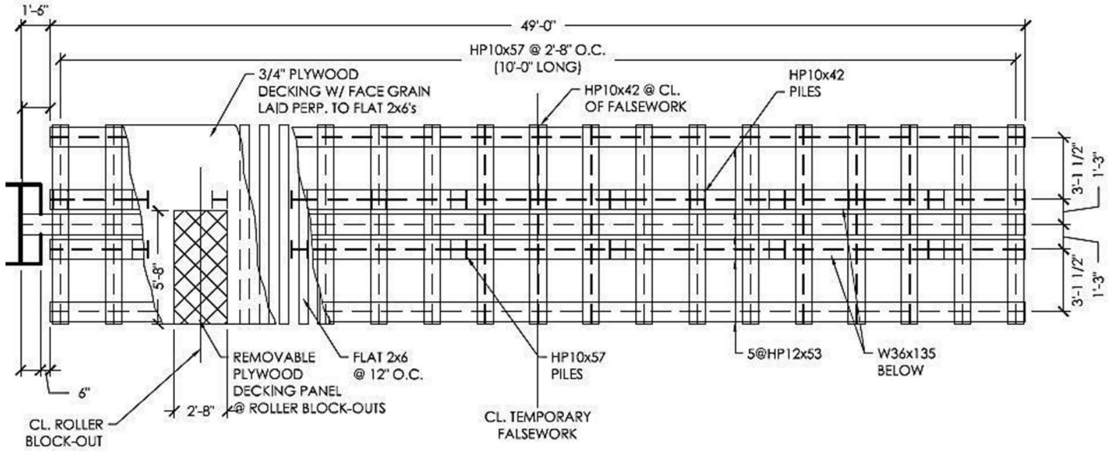
The new bridge superstructure was built on a set of temporary structures, which were constructed on the south side of the existing bridge. IA-92 traffic was detoured for nine days during the demolition of the existing bridge, construction of the new bridge foundation with precast substructure components, and the rolling and placement of the new bridge superstructure. Several specifications and codes were used for temporary structure design. The steel design was performed in accordance with the AISC Steel Construction Manual, 14th Edition. The temporary structure design was performed in accordance with the AASHTO Guide Specification for Bridge Temporary Works, 1st Edition, with 2008 Interim Revisions. Additionally, the International Building Code, 2009 Edition, serviceability design standards were employed in the design of a temporary wooden deck used for providing workers access to the superstructure.

The height of the temporary structures was approximately 10 ft. Each temporary structure consisted of three levels of steel beams that were constructed perpendicular to each other and connected to two lines of extended piles, labeled as interior (HP 10×57) and exterior (HP 10×42) (Figure 2-34). A W 36×135 beam was supported on each row of the extended piles.

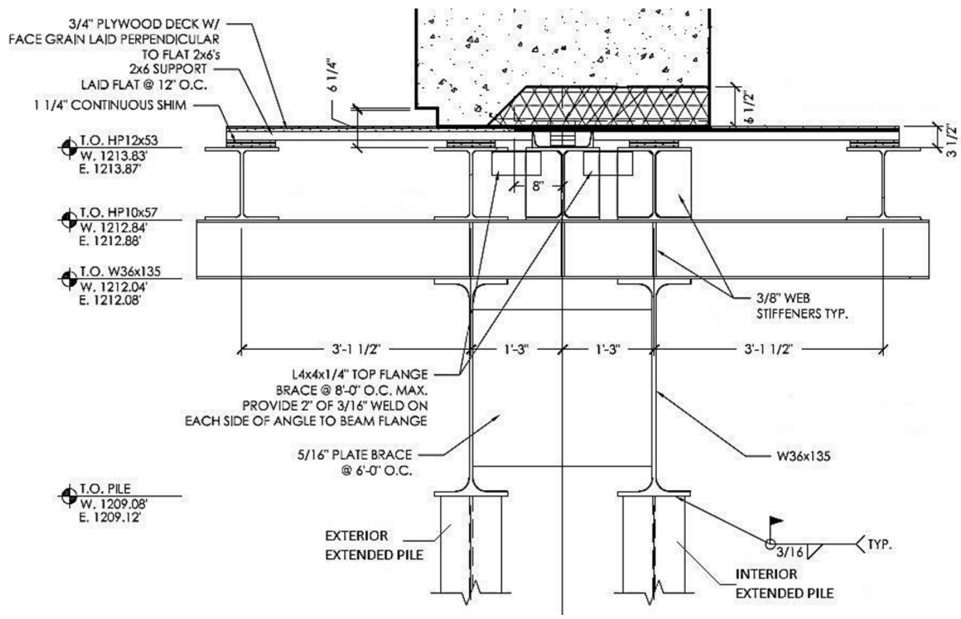
On top of these two beams, HP 10×57 beams were placed perpendicularly at 2 ft 8 in. spacing. Likewise, five HP 12×53 beams that extended the entire length of the temporary substructure were placed on top of the HP 10×57 beams. A temporary wooden deck was fabricated on top of the HP 12×53 beams to provide the construction crew access to the work area and to place equipment (Figure 2-34). Table 2-14 provides a summary of the new bridge superstructure weight and the temporary substructure details. Since the height of the extended piles was relatively short, bracing was not provided.

Table 2-14. Massena Bridge Temporary Structure Details

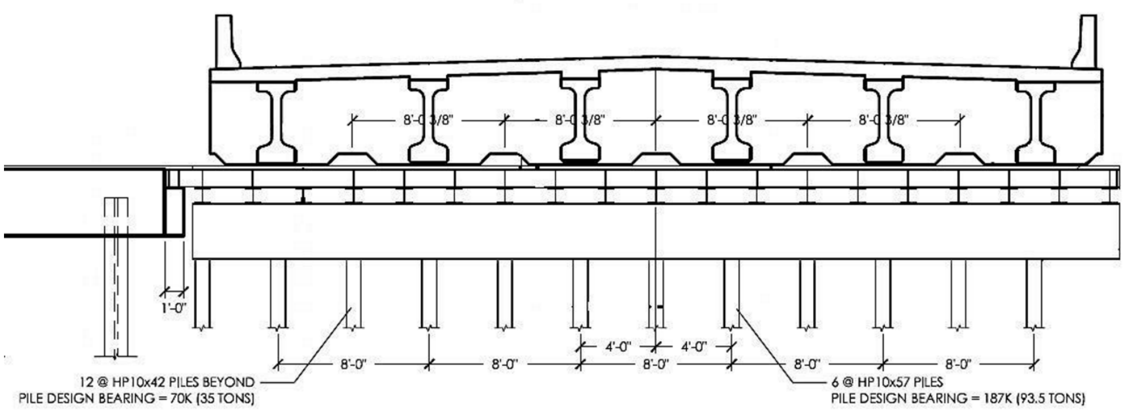
Total weight of the superstructure per span (tons)	721.00
Interior extended pile	
Type	HP 10 × 57
Spacing (ft)	8.00
Max. unbraced height (ft)	5.00
Exterior extended pile	
Type	HP 10 × 42
Spacing (ft)	4.00
Max. unbraced height (ft)	5.00



(a) Plan view



(b) End view



(c) Side view

Figure 2-34. Plan, end, and side views of Massena Bridge temporary structure

2.6.2 Design Standards for SIBC Temporary Structures

Following the temporary works failure during construction of the 1989 Maryland Route 198 over Baltimore-Washington Parkway bridge, an FHWA study in 1991 looked into the current practices employed by States for designing, constructing, and inspecting temporary works used in bridge construction. The study indicated that the comprehensiveness of specifications and design guidelines for temporary works used in bridge construction varied between state highway agencies. In response to the apparent need for unified design criteria and standards for temporary works used in bridge construction, AASHTO produced the *Guide Design Specification for Bridge Temporary Works* and the *Construction Handbook for Bridge Temporary Works* in 1995. In 2007, the failure of the I-35 W Bridge in Minnesota initiated the interim revisions in 2008 to the AASHTO Bridge Temporary Works in order to address any insufficiencies in the specifications and design guidelines (Surdahl et al. 2010).

Through the ABC implementation, such as the use of SPMT moves and SIBC, the need for designing new temporary works has emerged. Some of the design, construction, and inspection aspects of these new temporary works in bridge construction are not thoroughly addressed in the latest AASHTO publications (*Guide Design Specification for Bridge Temporary Works* and *Construction Handbook for Bridge Temporary Works,* 1st Ed., with 2008 Interim Revisions); therefore, future revision to the specifications will be required. Through the shortcomings highlighted in the subsequent sections in this chapter, agencies can initiate action to address specification insufficiencies in order to improve temporary work design and construction for future ABC projects.

2.6.2.1 Loads, Load Types, and Load Combinations

An overview of information is presented in this section for loads, load types, and load combinations that need to be revised in the 2008 AASHTO Guide Specification for Bridge Temporary Works. More specifically descriptions are on the omission of forces during the structural analysis, guidance for the application of different design specifications, and design areas that require formulation in regards to factors of safety.

2.6.2.1.1 Loads

The superstructure moving process in SIBC generates dynamic forces that are not addressed in the loading guidelines from the 2008 AASHTO Guide Specification for Bridge Temporary Works. The friction produced during the moving process of the new bridge superstructure generates shear and tensile forces, while the rotation of the superstructure caused by non-uniform forces during moving generates transverse forces in the temporary substructure. Additionally, based on the moving technique, push or pull, forces from the mechanical moving system could also be transferred to the temporary substructure. The temporary substructure is designed with rigid connections in order resist all movement generated from shear, flexural, and axial loading. The extended piles of the temporary substructure are subjected to biaxial bending and simultaneous flexural and axial loading from friction during the moving process. Members need to be treated as beam-columns. With beam-columns, a secondary moment is produced, which promotes the susceptibility to lateral torsional buckling. Therefore, all the potential forces produced during the superstructure moving process are not typically taken into account in the temporary substructure design.

2.6.2.1.2 Load Types

Temporary substructure needs to be designed in accordance with the AASHTO LRFD Bridge Design Specifications when new superstructure is used as a detour in temporary alignment. In general, design of temporary structures is performed as per the AASHTO Guide Specifications for Bridge Temporary Works (1995); design provisions of this specification are still based on ASD. Design of temporary substructures in SIBC projects are not specifically addressed in the AASHTO LRFD Bridge Design Specifications or the AASHTO Guide Specifications for Bridge Temporary Works.

When the temporary substructure is not utilized as a bypass and is based on the type of connection design between the temporary and the permanent structure, some connection components may be designed as per the ASD, while the others are designed following the AASHTO LRFD. In this type of connection, a composite connection is constructed which provides anchorage between the two structures. This allows for tension, shear, and transverse forces experienced by the temporary substructure to be transferred to the permanent structure. The composite components connected to the permanent structure may be subjected to loads from the distribution of live loads from traffic. Yet, these composite components are designed in respect to ASD rather than AASHTO LRFD. This is because the components are temporary and will be removed upon the construction completion. On the other hand, permanent structure reinforcement in the vicinity of the composite connection, which transfers the forces from the temporary substructure to the permanent structure, is designed in accordance to AASHTO LRFD. Also, the permanent structure reinforcement in the vicinity of the composite connection needs to be checked in order to determine if the reinforcement strength is adequate to withstand forces transferred from the temporary substructure.

Additionally, if site conditions are not suitable for the rehabilitation or reconstruction of the foundation while maintaining traffic on the existing bridge, two options are available: (1) close down the existing bridge and detour traffic to an alternative roadway, or (2) detour existing traffic on the new bridge superstructure while on the temporary location. Many SIBC projects choose to detour traffic to an alternative roadway during reconstruction of the foundation because of concerns related to the cost of designing and constructing the temporary substructure in accordance to AASHTO LRFD for temporarily traffic loads. The alternative traffic maintenance method was typically employed in SIBC projects that had significant traffic volumes and no viable alternative detour roadways. These constraints influenced the use of the temporary substructure and the new bridge superstructure as a temporary traffic detour. However, the actual change in cost might not be substantial for using the temporary substructure as a bypass and possibly could be a better alternative to shutting down the bridge and detouring traffic for months.

The temporary substructure design, material, and construction costs will escalate if traffic is routed to the new superstructure in temporary alignment. The increase in construction cost is primarily from D1.5 bridge welding code requirements. Design costs increase from the complications and uncertainties in using two different design provisions of AASHTO LRFD Bridge Design Specifications and AASHTO Guide Specifications for Bridge Temporary Works.

With the addition of traffic live loads, the connection requirements in the structural design will most likely be different. This will influence the cost of the temporary substructure the most. Comparing fillet weld connections between the two design methods, there is a difference between the minimum weld thicknesses. AASHTO LRFD requires the same weld thickness when the thinner of two welded base materials is 0.75 in. or less, whereas ASD allows for smaller weld thicknesses to be used for welded base materials smaller than a 0.75 in. The comparison between the minimum fillet weld requirements between AASHTO LRFD and ASD are shown in Table 2-15. Based on the comparison, when the thinner welded material thickness is 0.25 in. or 0.5 in., AASHTO LRFD requires 2.0 and 1.3 times more weld thickness than ASD, respectively. The AASHTO LRFD requirement for increased weld thickness might not generate substantial cost difference in the temporary substructure since the addition of traffic live loads could require a weld thickness that equals or exceeds the required weld size. The minimum effective fillet weld length between the two design specifications is the same which is the maximum between four times the nominal weld size and 1.5 in. The difference between the minimum weld thicknesses and the minimum effective weld length required will not be affected.

Table 2-15. A Comparison of Minimum Fillet Weld Requirements

AASHTO LRFD		ASD	
Thinner Base Material Thickness (in.)	Minimum Fillet Weld (in.)	Thinner Base Material Thickness (in.)	Minimum Fillet Weld (in.)
		≤ 1/4	1/8
		1/4 to 1/2	3/16
≤ 3/4	1/4	1/2 to 3/4	1/4
> 3/4	5/16	> 3/4	5/16

Additionally, the AASHTO LRFD and ASD employ two different American Welding Society (AWS) standards; AASHTO LRFD requires AWS D01.5 Bridge Welding whereas ASD requires AWS D01.1 Structural Welding (Steel). The basic cost per inch of weld is determined by the labor and overhead cost, filler material cost, and shielding gas cost. For the filler material, the base metal determines the type of material that can be used during the welding process. Yet, this is not a factor since the base metals used by the two welding codes are very similar. The base metals of both welding specifications incorporate carbon or low alloy steel, specify a 1/8 in. minimum thickness up to an unlimited thickness, and require that a minimum specified yield strength cannot be greater than 100 kip/in^2. As noted earlier, AASHTO LRFD requires a larger minimum weld thickness when the thinner welded base material thickness is 0.5 in. or smaller; however, the filler material cost of the weld would not be a significant factor influencing the overall welding cost as compared to welding labor cost. The factors that could potentially influence labor cost consist of inspection, welding process, and level of certification.

Welding inspection can occur during the welding process and/or after completion of the weld. Most often, inspection occurs during the welding process to ensure that multiple welding steps and tolerances are adhered. When the weld is completed, visual inspections is performed to assess the correct weld size, changes in surface discontinuity, and any defects. Typically, fillet field welds are applied for connecting the members of the temporary substructure. The acceptance criteria for visual inspection of fillet welds between the welding specifications are identical: (1) crack free, (2) the weld length and size shall not be less than required, (3) craters shall be filled, (4) weld profile shall conform to requirements, and (5) base metal undercut shall not exceed 1/32 in. The major factor that influences welding inspection labor cost are the inspection requirements called out in the contractual documents: the type of inspection, the frequency of inspection, and the documentation for those inspections. Subsequently, the fundamental difference influencing changes in inspection labor cost is the inspection requirements specified in the contractual documents, which vary based on project type.

The time to place a weld is determined by the welding process requirements stated in project and welding code specifications. The welding process can influence the cost since some welding processes take longer. These welding processes are highly validated, follow a restricted control procedure, are unique to every project, and require a lengthy procedure to establish. Before any welding is performed, the welding contractor needs to first establish a welding a procedure. This welding procedure is formulated based on what is called for in the project and the welding code specifications. Next, a weld procedure qualification testing cycle is performed in order to verify that the proposed welding process is adequate. This procedure includes physical and mechanical testing required by welding codes and could include break and bend samples, along with ultrasonic and radiographic testing. Once the welding process is validated, the welders must pass a certification test based on the welding processes established. The certification test is a performance evaluation, which requires welders to produce an acceptable weld to code conditions with certain thicknesses and types of materials, welding machines, and electrode combinations. After that, a welding procedure sheet is produced for the welders to follow. That same procedure sheet is utilized for welding the components of the structure. The welding procedure sheet is essentially a recipe that spells out the type of electrode, if there is shielding gas involved, type of shielding gas, flow rate of shielding gas, sequence of weldment, and much more. The main aspect that changes between welding specifications are the tolerances of the welding processes such as gas flow and electrical settings. The AWS D01.5 Bridge Welding code is more of a prescribed weld in order to predict consistency of weld outcome amongst different welders. This essentially means that the bridge welding codes restrict the number of variables that a welder can freely change during the welding process. Specific welding process requirements that could influence differences in welding time between the two welding codes are out of the scope of this report and will not be investigated any further.

Furthermore, differences in welder certification would not influence a change in cost in regards to the use of temporary substructure as a bypass, since many welders certification tests are based on the positional plane that they are allowed to weld in: horizontal or vertical. For example, if welders take a flat plate weld test, all they can weld is in the flat position. Any weld produced outside of that position is out of code. Therefore, if the temporary substructure is used as a detour, the need for more qualified welders would not be required; only the welding process employed would change.

2.6.2.1.3 Load Combinations

It would be ideal for the driven pile foundation of the temporary substructure to be designed with capacity to prevent settlement before, during, and after construction of the superstructure; however, this not always an attainable goal. Anticipated immediate settlement of the temporary substructure when the full bridge superstructure loads are applied needs to be calculated in order to ensure a level transition between the temporary substructure and the permanent structure. The factor of safety for foundations is greater than other structure components. Also, the foundation's factor of safety is not constant and varies based on the site conditions and function. Typically, the downward loading factors of safety for traditional foundation piles range from 2.0 to 3.5 based on the construction control method employed

(Coduto 2001). However, unlike traditional foundations, the driven pile foundation of the temporary substructure is only utilized over a period of several months and may not require the same factor of safety magnitude. Long-term settlement such as consolidation and secondary compression settlement will probably not develop in the temporary driven pile foundation during the SIBC project. Currently, the 2008 AASHTO Guide Specification for Bridge Temporary Works does not provide any recommendations for the factor of safety concerning temporary pile foundations. Therefore, future revisions should incorporate recommendations for factors of safety for temporary file foundations based on the site conditions and their function in the construction project. Additionally, multiple factors of safety should be provided since the type and magnitude of forces that the temporary substructure experiences change between the different SIBC construction phases.

2.6.2.1.4 Deflection Limits and Tolerances

It is important to control the deflection and twist of the superstructure components during lifting, transporting, and placement operations in order to limit additional stresses in the bridge superstructure, which can overload the structure. Some road agencies define allowable tolerances for deflection and twist of the superstructure span in their project special provisions that the contractor must adhere to. Likewise, these allowable tolerances for deflection and twist of the superstructure span must be followed during the rolling or sliding of the superstructure to its permanent location. Assuming that the superstructure and temporary substructure deflections are correlated, it can be conservatively presumed that the temporary substructure supporting the superstructure must be designed for a maximum deflection within the allowable tolerances for superstructure span deflection and twist specified in the special provisions. Tolerances for deflection from several project special provisions can be viewed in Table 2-16.

Table 2-16. Deflection Tolerances in SIBC Project Special Provisions

State	Project Name	Year	Special Provisions: Deflection Tolerance (in.)
Iowa	Messena Bridge	2013	0.25
Maine	Littlefields Bridge	2013	0.25
Nevada	West Mesquite Interchange at I-15	2012	0.20
New York	I-80 over Dingle Ridge Road	2010	0.25
Oregon	OR-213 Jughandle	2012	0.25
Utah	Summit Park Bridge	2011	0.25
Utah	Wanship Bridge	2012	0.25
Wisconsin	WIS 29 EB Bridge	2011	0.25

According to Table 2-16, a 0.25 in. deflection and twist tolerance of the superstructure components is commonly employed. The AASHTO Guide Specification for Bridge Temporary Works should potentially adopt the maximum deflection tolerance of 0.25 in. for heavy-duty shoring systems if the assumption of deflection correlation between the superstructure and the temporary substructure is determined to be valid. Also, an additional maximum deflection tolerance should be investigated when the temporary substructure is utilized as a detour.

2.7 SUMMARY

A total of 123 completed ABC projects are reviewed, including 76 PBES, 30 SIBC, and 11 SPMT moves. In addition to other literature, the project documentation was used as the primary source of information.

2.7.1 Project Scoping Parameters

Based on the information from the completed ABC projects and research advisory panel input, project scoping parameters are identified. These parameters are arranged in hierarchical order to develop a decision-making framework for evaluating CC, PBES, SPMT move, and SIBC project delivery alternatives for a given site. A detailed description of the scoping parameters and the decision-making framework is presented in Chapter 3.

2.7.2 Foundations

Foundation types commonly used for highway bridges, advantages and limitations of using these foundation types at a particular site (in the context of ABC), extent of implementation of different foundation types in ABC projects, and the foundation policies of the states that implemented a large number of ABC projects are reviewed. In addition, the foundation and substructure construction while the existing bridge is in service and retrofit of existing structures are reviewed. The information from this review is used to develop specific recommendations presented in Chapter 4 for constructing foundations while the existing bridge is in service.

2.7.3 Cost Benefit Parameters

The completed ABC projects listed in Table 2-1 are reviewed, and cost parameters are identified. The data from the same projects is used to develop cost calculation models and to calculate specific costs for CC, PBES, SPMT move, and SIBC. In addition, the benefit parameters are identified from the list of project scoping parameters. A detailed description of the cost parameters, cost calculation models, specific costs, benefit parameters, and the process for cost-benefit analysis of ABC projects is presented in Chapter 5.

2.7.4 Bridge Slide Mechanisms and Operation Parameters

Bridge sliding mechanisms and slide operation parameters, including friction at the PTFE-steel sliding surface, are reviewed. Review of the completed ABC project in Table 2-1 shows that only force control procedures are utilized to pull or push a new superstructure onto the final position. This process creates complications and challenges. The displacement control method with force monitoring has many advantages over the force control method, though not yet implemented in sliding bridges. Based on the PTFE-steel interface friction data presented in literature, static friction of 10% and kinetic friction of 5% are selected to be representative, and they are specified in the analysis presented in Chapter 6. Further, Chapter 6 presents bridge slide simulation using force and displacement control procedures to demonstrate the advantages and limitations of using such methodology in SIBC.

2.7.5 Temporary Structure Design and Construction

Temporary structures constructed for eight SIBC projects are reviewed and documented. The documented temporary structure layout and characteristics are helpful for identifying potential temporary structure details for a given site. In addition, several temporary structure designs are reviewed. Review of implemented projects as well as the pertinent design specifications and guides highlighted the insufficiencies with respect to loads, load types, load combinations, and deflection tolerances given in the 2008 AASHTO Guide Specification for Bridge Temporary Works. The identified insufficiencies need to be addressed in future updates to the current temporary structure design specifications.

3 FRAMEWORK FOR SCOPING ABC PROJECTS

3.1 OVERVIEW

The multi-criteria decision-making framework was developed during the last phase of this project to comparatively assess CC vs. ABC. The decision making framework was customized for implementation in Michigan and supplemented with a guided software program titled Michigan Accelerated Bridge Construction Decision-Making (Mi-ABCD) tool. In the current version of Mi-ABCD, the ABC only reflects PBES project delivery alternatives. New ABC technologies, such as SPMT move and SIBC, are being increasingly implemented throughout the U.S. In Michigan, SIBC was implemented in two pilot projects involving three bridge replacements. To address the need, the existing decision-making process is advanced to assess four project delivery alternatives (CC, PBES, SPMT move, and SIBC) as part of the project scoping process for a site. In addition, the scoping process of the decision- making framework has been significantly modified to consider all the site specific and general parameters that affect the project delivery as well as the long term performance of the bridge. This chapter provides the scoping framework and associated guidelines for its implementation.

3.2 SCOPING FRAMEWORK GUIDELINES FOR CC, PBES, SPMT MOVE AND SIBC ALTERNATIVES

The decision-making framework for Mi-ABCD was developed based on a comprehensive literature study of decision-making models and methodologies, experience gained from implementation and demonstration projects, and an extensive interaction with the MDOT Project Research Advisory Panel (Aktan and Attanayake 2013). The process is updated to incorporate SPMT move and SIBC project delivery alternatives; thus, providing assistance to scope projects for implementing CC, PBES, SPMT move and SIBC alternatives.

The SPMT move and SIBC specific parameters are incorporated in the existing decision-making process and rearranged to form a new set of decision-making parameters (discussed in Section 3.2.1). The parameters are grouped as, quantitative and qualitative. The quantitative parameters influence the decision-making based on project specific data. The project specific data in the current decision-making process is enhanced to include additional parameters specific to SPMT move and SIBC alternatives. In addition, costs parameters associated with SPMT move and SIBC alternatives are included, and the user cost and life-cycle cost methodologies are updated (discussed in Chapter 5). On the other hand, the qualitative parameters are incorporated in the decision-making based on user preferences that are described as 'preference ratings'. Similar to the earlier Mi-ABCD methodology, Ordinal Scale Ratings (OSRs) are implemented to enable alternative analysis using the Analytical Hierarchy Process (AHP) (Aktan and Attanayake 2013). The OSRs are defined on a scale of 1 to 9 and eliminate the need for pair-wise comparison of parameters and project alternatives, required in the AHP methodology.

The quantitative parameters are associated with project specific data; hence, the data can be obtained during the project planning stages. To facilitate a project specific data collection process, the data is separated into three groups: (1) site-specific, (2) traffic, and (3) cost (discussed in Section 3.3).

Some of the required data, such as costs related to ABC, is extracted from a database developed in this project from nationwide ABC implementations. This database can be updated from future implementations to improve the accuracy and reliability of the decision-making results. For example, the cost data can be calculated from the database containing unit costs from completed ABC projects, and can be revised with the data from future implementations. The traffic data and detour length are available in other sources such as the bridge management databases. Further, *general data* (i.e., site characteristics and economic indicators) for a county or a region can be incorporated in the process for converting the quantitative data into ordinal scale ratings to develop AHP pair-wise comparison matrices, similar to the earlier methodology of Mi-ABCD.

The users are able to provide unambiguous judgments for qualitative parameters during the project planning stages based on the *context* of each qualitative parameter. The *context* is defined to represent possible situations/conditions at a site that are associated with ranges of OSRs and different levels of preferences (discussed in Section 3.4). The user preferences based on the situations/conditions at the site will represent the OSRs for the qualitative parameters.

In the Mi-ABCD methodology, the user needs to decide how each decision parameter is correlated to the project delivery alternatives. For example, if a particular parameter is of *moderate significance*, then with respect to this parameter, it becomes a project delivery alternative that is either *moderately preferred* (i.e., directly correlated) or *moderately not preferred* (i.e., inversely correlated). To facilitate this process, correlations are predefined for a few quantitative parameters. For the rest of the quantitative parameters, the correlations are kept dynamic as they are based on the project specific data and the calculated values, as presented in Section 3.3. For the qualitative parameters, the correlations are predefined, as presented in Section 3.4. The user can override the predefined correlations during the scoping process.

The user can implement the process (scoping framework) as a multi-user platform to compile input data, perform calculations, and develop reports. The users can compare two, three, or four alternatives among CC, PBES, SPMT move, and SIBC during scoping for a bridge replacement project. Once a multi-user platform is developed, the process can be automated to assign an OSR of *1* for the qualitative parameters that pertain to the unselected alternative(s). Similarly, for the quantitative parameters, the data items pertaining to the unselected alternative(s) can be deactivated and assigned an OSR of *1*.

Ultimately, by entering the quantitative data and qualitative preferences into the upgraded framework and implementing the Mi-ABCD methodology, the users can identify the optimal project delivery alternative (among CC, PBES, SPMT move, and SBIC) for a given site.

3.2.1 Scoping Parameters

A set of scoping parameters is developed related to CC, PBES, SPMT move, and SIBC project delivery alternatives. The parameters specific to SPMT move and SIBC alternatives are developed by the extensive analysis of the completed ABC projects (FHWA 2015; ABC center 2014), ABC policies of DOTs (MassDOT 2009; JLARC 2010; IowaDOT 2012; VDOT 2012; WisDOT 2013; MDOT 2013a; MDOT 2014a) and related literature (FHWA 2007; UDOT 2009; MDOT 2013b; UDOT 2013; Shutt 2013a, b, c; FHWA 2013a; Aktan et al. 2014; FHWA 2014; MDOT 2014b). The parameters were scrutinized and, following several revisions, arranged in a hierarchical manner as major-parameters, sub-parameters, and secondary-level sub-parameters (Figure 3–1). These parameters are evaluated for a bridge replacement or rehabilitation project based on project specific data (discussed in Section 3.3) and user preferences (discussed in Section 3.4).

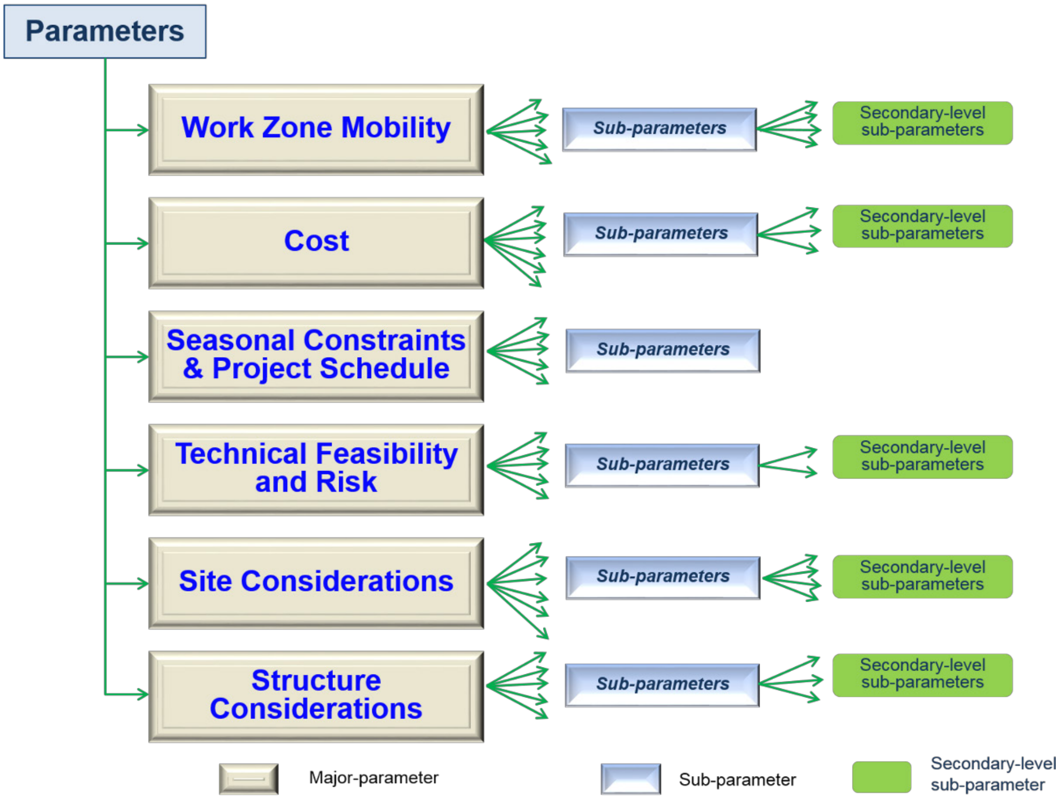


Figure 3–1. Arrangement of scoping parameters

There are six major-parameters: (i) Work Zone Mobility (WZM), (ii) Cost, (iii) Seasonal Constraints and Project Schedule (SC&PS), (iv) Technical Feasibility and Risk (TF&R), (v) Site Considerations (STE), and (vi) Structure Considerations (STR). The twenty-five sub-parameters are shown in Table 3–1. Some of the sub-parameters also include secondary-level sub-parameters as shown in Table 3–2 through Table 3–7. The secondary-level sub-parameters are needed because detailed consideration is necessary to compare ABC alternatives of PBES, SPMT move, and SIBC. The sub-parameters shown in Table 3–1 have secondary-level sub-parameters, except a few that are indicated as without secondary-level sub-parameters. The secondary-level sub-parameters include both quantitative and qualitative parameters. The order of arrangement of the parameters has no significance.

Table 3–1. Decision-Making Parameters for Comparing Project Delivery Alternatives

Major-Parameters	Work Zone Mobility (WZM)	Cost	Seasonal Constraints and Project Schedule (SC&PS)	Technical Feasibility and Risk (TF&R)	Site Considerations (STE)	Structure Considerations (STR)
Sub-Parameters	Significance of facility carried traffic	Direct	Stakeholders limitations*	Risks	Site vicinity	Existing superstructure
	Lane closure considerations	Indirect	Seasonal limitations*	Contractor experience	Staging area and travel path	Existing substructure/foundation
	Detour considerations	Alternative Specific Cost	Construction duration (days)**		Feature Intersected (FI)	Span
	Significance of feature intersected traffic				Limitations for SIBC	Limitations for PBES construction*
					Site condition complexities* (e.g., Viaduct over rapids, deep valley, or restricted site access) [Terrain to traverse]	Geometric complexity for SPMT move* (e.g., ramps, large skew, etc.)
					Scour or hydraulic complexities*	
					Environmental protection near and within the site* (e.g., wetland)	
					Aesthetic requirements*	

Note: Each sub-parameter shown above contain secondary-level sub-parameters, except the following:

* Qualitative sub-parameter without secondary-level sub-parameters

** Quantitative sub-parameter without secondary-level sub-parameters

The following sections describe the major-parameters, sub-parameters, and secondary-level sub-parameters (Table 3–2 to Table 3–7) defined for scoping a bridge replacement or rehabilitation project. In Table 3–2 to Table 3–7, sub-parameters containing secondary-level sub-parameters, quantitative sub-parameters, and qualitative sub-parameters are indicated. Note that *Italic* font is used to represent the secondary-level sub-parameters in Table 3–2 to Table 3–7.

3.2.2 Work Zone Mobility (WZM)

The following are the four sub-parameters that are associated with the WZM major parameter:

- **Significance of facility carried (FC):** Considers the importance of maintaining traffic on FC. The focus is on the level of service (LOS) during construction and the impact on nearby intersections or grade crossings due to closure of FC.
- **Lane closure considerations:** Consider the lane closure feasibility on the FC before the ABC window (i.e., full closure of the traffic) and lane closure feasibility on FI before and during the ABC window.
- **Detour considerations:** Consider the availability of detour, length of detour, and the LOS on detour during lane or full closure of FC and FI before and during the ABC window.
- **Significance of feature intersected (FI) traffic:** Considers the importance of maintaining the FI traffic. The focus is on the level of service (LOS) during construction and the impact on nearby intersections or grade crossings due to closure of FI.

Table 3–2 shows the WZM major parameter, the associated sub-parameters, and the secondary-level sub-parameters.

Table 3–2. Work Zone Mobility Parameters

Major-Parameter	Work Zone Mobility (WZM)		
Sub-Parameters& *Secondary-level sub-parameters*	Significance of facility carried (FC)†		
	LOS on FC§	*Impact on nearby major intersection/ highway-rail grade crossing with full closure*	
	Lane closure considerations		
	Closure of curb-lanes on the bridge¥	*Lane closure/traffic shift restrictions on FI*	
	Detour considerations		
	Detour availability	*Detour length*	*LOS on detour*
	Significance of feature intersected (FI) traffic		
	LOS on FI	*Impact on nearby major intersection/highway-rail grade crossing due to FI traffic*	

†Sub-parameters containing secondary-level sub-parameters
§ Quantitative sub-parameters
¥ Qualitative sub-parameters

3.2.3 Cost

The three sub-parameters that are associated with the Cost major-parameter are as follows:

- **Direct cost:** Considers the costs that incur during the construction of the bridge. Generally, these costs are directly incurred by the agency or by the general contractor in a design-build project. For detour duration of more than 2 weeks, the cost of upgrading the detour route is also considered under this sub-parameter and included in the maintenance of traffic (MOT) cost.
- **Indirect cost:** Considers the costs that are not directly related to project cost.
- **Alternative specific cost:** Considers the costs related to implementing specialty technology such as SPMT move or SIBC.

Table 3–3 shows the cost major parameter, the associated sub-parameters, and the secondary-level sub-parameters.

Table 3–3. Cost Parameters

<table>
<tr><th>Major-Parameter</th><th colspan="6">Cost</th></tr>
<tr><td rowspan="13">Sub-Parameters& Secondary-level sub-parameters</td><td colspan="6">Direct Cost†</td></tr>
<tr><td colspan="2">Construction§</td><td colspan="2">Maintenance of traffic (MOT)</td><td colspan="2">Utility relocation</td></tr>
<tr><td colspan="6">Indirect Cost</td></tr>
<tr><td colspan="3">Life-cycle</td><td colspan="3">User</td></tr>
<tr><td colspan="3">Economic impact on surrounding Communities</td><td colspan="3">Economic impact on surrounding businesses¥</td></tr>
<tr><td colspan="6">Alternative Specific Cost</td></tr>
<tr><td colspan="3">SPMT Move Specific</td><td colspan="3">SIBC Specific</td></tr>
<tr><td colspan="3">Specialty equipment/contractor</td><td colspan="3">Specialty contractor</td></tr>
<tr><td colspan="3">Mobilization</td><td colspan="3">Equipment & accessories</td></tr>
<tr><td colspan="3">Preparing travel path</td><td colspan="3">Preparing & operating</td></tr>
<tr><td colspan="3">Preparing staging area</td><td colspan="3">Temporary structures</td></tr>
<tr><td colspan="3">Temporary structures</td><td colspan="3"></td></tr>
</table>

†Sub-parameters containing secondary-level sub-parameters
§ Quantitative sub-parameters
¥ Qualitative sub-parameters

3.2.4 Seasonal Constraints and Project Schedule (SC&PS)

The following are the three sub-parameters that are associated with the SC&PS major-parameter:

- **Stakeholders' limitations:** Consider the limitations imposed by the stakeholders on the construction window of a bridge rehabilitation or replacement project.
- **Seasonal limitations:** Consider the likely weather events that will impact the on-site construction schedule.
- **Construction duration:** Considers the on-site construction duration of each project delivery alternative. This also represents the duration of detour for respective project delivery alternative. This sub-parameter is used to calculate user cost and life-cycle cost. Based on this sub-parameter, the project delivery alternative with least duration is assigned high preference.

For the SC&PS major parameter, the sub-parameters do not have secondary-level sub-parameters. Table 3–4 shows the SC&PS major-parameter and associated sub-parameters.

Table 3–4. SC&PS Parameters

Major-Parameter	Seasonal Constraints and Project Schedule (SC&PS)
Sub-Parameters	Stakeholders limitations¥
	Seasonal limitations¥
	Construction duration (days)§

¥ Qualitative sub-parameters
§ Quantitative sub-parameters

3.2.5 Technical Feasibility and Risk (TF&R)

The following are the two sub-parameters that are associated with the TF&R major-parameter:

- **Risks:** Consider the obstacles associated with each of the project delivery alternatives. It recognizes that new/innovative construction methods can be of higher risk and higher cost.
- **Contractor experience:** Considers the contractor and manufacturer experience and qualifications for each of the project alternatives.

Table 3–5 shows the TF&R major parameter, the associated sub-parameters, and the secondary-level sub-parameters.

Table 3–5. TF&R Parameters

Major-Parameter	Technical Feasibility and Risk (TF&R)	
Sub-Parameters& *Secondary-level sub-parameters*	Risks†	
	Financial and political¥	*Traffic within work zone*
	Contractor experience	
	Contractor/ Specialty contractor qualifications	*Manufacturer/ Precast plant experience*

†Sub-parameters containing secondary-level sub-parameters
¥ Qualitative sub-parameters

3.2.6 Site Considerations (STE)

The following are the eight sub-parameters that are associated with the STE major-parameter:

- **Site vicinity:** Considers the availability of staging area and several other parameters that impact SPMT move implementation.
- **Staging area and travel path:** For SPMT move, this considers the conditions at the staging area and travel path. For PBES, this sub-parameter considers the availability of storage at the site.
- **Feature intersected (FI):** Considers aspects of FI that impact SPMT move, SIBC, or PBES implementation.
- **Limitations for SIBC:** Consider the aspects that may complicate implementation of SIBC.
- **Site condition complexities**: Consider the site condition difficulties for access, equipment deployment or a specific construction technology. The examples of site condition complexities include viaduct over rapids, deep valley, restricted site access, etc.
- **Scour or hydraulic complexities**: Consider the complexity related to dealing with the scour issues.
- **Environmental protection near and within the site**: Considers the site conditions with wetlands, endangered species, natural vegetation, etc., that require environmental protection requiring environmental reviews and/or permits.
- **Aesthetic requirements**: Consider the location or region of the bridge, and associated cultural and historical significance. It is presumed that the architectural concepts are cheaper to implement in CC than PBES, and a bridge superstructure constructed on temporary supports for SPMT move and SIBC emulates CC. Also, CC can address the cultural and historical significance.

Table 3–6 shows the STE major parameter, the associated sub-parameters, and the secondary-level sub-parameters.

Table 3–6. Site Considerations Parameter

<table>
<tr><th>Major-Parameter</th><th colspan="5">Site Considerations (STE)</th></tr>
<tr><td rowspan="13">Sub-Parameters&
Secondary-level sub-parameters</td><td colspan="5">Site vicinity†</td></tr>
<tr><td>*Procuring distance of specialty equipment§*</td><td colspan="2">*Number of clustered bridge replacement projects*</td><td colspan="2">*Availability of staging area*</td></tr>
<tr><td colspan="5">Staging area and travel path</td></tr>
<tr><td colspan="2">*Allowable ground bearing pressure*</td><td colspan="3">*Impact on overhead and underground utilities¥*</td></tr>
<tr><td colspan="2">*Environmental sensitivity of staging area*</td><td colspan="2">*Travel path complexity*</td><td>*Travel path slope*</td></tr>
<tr><td colspan="5">Feature intersected (FI)</td></tr>
<tr><td colspan="2">*Significance of FI class
(e.g., freeway, arterial, etc.)*</td><td colspan="3">*ROW availability on FI for equipment staging for PBES*</td></tr>
<tr><td colspan="5">Limitations for SIBC</td></tr>
<tr><td>*Available ROW for SIBC*</td><td colspan="4">*Site constraints for parallel replacement-structure construction
(e.g., utilities, underclearance of FI, etc.)*</td></tr>
<tr><td colspan="5">Site condition complexities
(e.g., Viaduct over rapids, deep valley, or restricted site access) [Terrain to traverse]</td></tr>
<tr><td colspan="5">Scour or hydraulic complexities</td></tr>
<tr><td colspan="5">Environmental protection near and within the site (e.g., wetland)</td></tr>
<tr><td colspan="5">Aesthetic requirements</td></tr>
</table>

†Sub-parameters containing secondary-level sub-parameters
§ Quantitative sub-parameters
¥ Qualitative sub-parameters

3.2.7 Structure Considerations (STR)

The following are the five sub-parameters that are associated with the STR major-parameter:

- **Existing superstructure:** Considers underclearance, grade, utilities on the existing superstructure, and the staged construction feasibility.
- **Existing substructure/foundation:** Considers the reuse potential of the existing substructure or foundation. It also considers the challenges associated with the construction of substructure/foundation when the bridge is in service.
- **Span:** Compares the existing maximum span with the new maximum span and the number of similar spans for the new bridge.
- **Limitations for PBES construction**: Considers the availability of specialized materials required for PBES construction, and restrictions in transporting and erecting PBES components of new superstructure.
- **Geometric complexity for SPMT move**: Considers the geometric features that constrain SPMT move implementation. The examples of geometric features include ramps, extreme skew, high grade on the FI, etc.

Table 3–7 shows the STR major parameter, the associated sub-parameters, and the secondary-level sub-parameters.

Table 3–7. Structure Considerations Parameter

<table>
<tr><th>Major-Parameter</th><th colspan="12">Structure Considerations (STR)</th></tr>
<tr><td rowspan="8">Sub-Parameters& Secondary-level sub-parameters</td><td colspan="12">Existing superstructure†</td></tr>
<tr><td colspan="3">Underclearance§</td><td colspan="3">Vertical grade/ slope</td><td colspan="3">Impact on utilities on the structure¥</td><td colspan="3">Feasibility of staged construction</td></tr>
<tr><td colspan="12">Existing substructure/foundation</td></tr>
<tr><td colspan="4">Reuse potential with or without improvements</td><td colspan="4">Complexity of constructing new foundation when bridge is in service</td><td colspan="4">Complexity of constructing new foundation when bridge is not in service</td></tr>
<tr><td colspan="12">Span</td></tr>
<tr><td colspan="6">New span length</td><td colspan="6">Number of similar spans</td></tr>
<tr><td colspan="12">Limitations for PBES construction</td></tr>
<tr><td colspan="12">Geometric complexity (e.g., ramps, large skew, etc.) for SPMT move</td></tr>
</table>

†Sub-parameters containing secondary-level sub-parameters
§ Quantitative sub-parameters
¥ Qualitative sub-parameters

3.3 QUANTITATIVE DATA

The quantitative parameters shown in Table 3–2 to Table 3–7 are identified based on the project specific quantifiable data that is available or calculated during the scoping process. A few parameters classified quantitative involve selecting an option from a list of inputs. For example, the *Detour Availability* requires selecting an option among: (1) available, and (2) unavailable. The significance of each quantitative parameter in the project scoping process and its correlation with the project delivery alternatives is described in Table 3–8. The correlations are required for developing pair-wise comparison ratings for the alternatives using the Mi-ABCD methodology from the calculated preference ratings (Aktan and Attanayake 2013). The correlations are decided following the analysis of completed ABC projects. As discussed in Section 3.2, the correlations are either *Directly Correlated* or *Inversely Correlated*. The *Directly Correlated* alternative(s) is the most preferred when preference rating of a corresponding parameter is the high (i.e., the OSR of 9), and is considered neutral when the preference rating of a corresponding parameter is low. On the other hand, the *Inversely Correlated* alternative(s) is the least preferred when the preference rating of a corresponding parameter is the high, and is considered neutral when the preference rating of a corresponding parameter is low.

Table 3–8. Significance of Quantitative Parameters and Associated Correlation with Project Delivery Alternatives

Major-Parameter	Sub-Parameter	Quantitative Parameter	Significance of the Parameter	Project Delivery Alternatives	
				Directly Correlated	Inversely Correlated
Work Zone Mobility (WZM)	Significance of facility carried (FC)	LOS on FC	The LOS is used to calculate a preference rating for the significance of FC as well as to decide the preferred project delivery alternatives.	*Correlation depends on the change in LOS from existing to during construction for each alternative. If the change in LOS is high with a particular alternative, then that alternative will be preferred less; whereas, if the change in LOS is low, then the alternative will be highly preferred.*	
		Impact on nearby major intersection/ highway-rail grade crossing with full closure	If the LOS at nearby major intersection/ highway-rail grade crossing during construction is low (E or F), then this parameter is assigned a higher preference, and vice versa.	PBES,SPMT Move, SIBC	CC
	Detour considerations	Detour availability	This identifies the significance of the detour and considers two cases: (1) detour is unavailable, and (2) detour is available. If case-1, then the parameters: “length of detour” and “ADT on detour” (discussed next) are assigned neutral preference (i.e., rating = 1). However, if case-2, then the preferences for those parameters are decided based on their respective values.	*In case-1 SPMT move and SIBC are assigned high preference. In case-2n CC, PBES, SPMT move and SIBC are assigned neutral preference.*	
		Detour length	This identifies the level of impact on the FC traffic that uses the detour route during construction.	SPMT Move, SIBC	CC, PBES
		LOS on detour	The LOS on detour route is used to calculate a preference rating for the impact on the detour route.	SPMT Move, SIBC	CC, PBES
	Significance of feature intersected (FI) traffic	LOS on FI	The LOS on FI is used to calculate a preference rating for the significance of FI as well as to decide the preferred project delivery alternatives based on the HCM procedure. Here the FI classification based on HCM is also considered. The calculated value of LOS is compared with the LOS of each project delivery alternative during construction.	*SPMT move is preferred if the FI is on the National Highway System classification and the change in LOS is high. CC, PBES, SIBC, and SPMT move are equally preferred if the FI is on the local roadway system and change in LOS is moderate.*	

		Impact on nearby major intersection/highway-rail grade crossing due to FI traffic	If a nearby highway-rail grade crossing is present, then the parameter considers the existing level of impact on the grade crossing. The level of impact ranges from A to F (i.e., very low to extremely high). If the level of impact during construction is high, then this parameter is assigned a high preference, and vice versa. Note: It is considered that SPMT move requires very few construction activities at the bridge location compared to CC, PBES and SIBC. Thus, SPMT move is considered more preferable.	SPMT Move	CC, PBES, SIBC
Cost	Direct Cost	Construction	This deals with initial construction cost excluding the maintenance of traffic (MOT) cost and specialty contractor and equipment cost.	*Correlation is dynamic. The alternative with the least cost will be directly correlated and the others will be inversely correlated.*	
		Maintenance of traffic (MOT)	This considers the average cost per day for MOT that is incurred by a highway agency or to the general contractor in a design-build project. Here, the MOT cost per day is calculated as a mean value irrespective of the project delivery alternative and may include MOT on detour, MOT on FI, and MOT on FC (such as part-width construction). The total MOT cost for each project delivery alternative is calculated by multiplying the mean MOT cost per day with the construction duration of each alternative. Additionally, for the alternatives requiring detour duration more than 2 weeks, the cost of upgrading the detour route is added to the respective total MOT cost.	*Correlation is dynamic. The alternative with the least cost will be directly correlated and the others will be inversely correlated.*	
		Utility relocation	This parameter considers the number of major utilities affected and the level of difficulty for relocation. The utility relocation cost is estimated based on the above data. It is identified that SPMT move implementation may require utility relocation and protection more than any other project delivery alternative. As the complexity and cost increases, this parameter is assigned a high preference, and vice versa.	SIBC, PBES, CC	SPMT Move

	Indirect Cost	Life-cycle cost	This parameter considers the present value of project total life-cycle cost (LCC) for each delivery alternative. This includes all the direct costs and user cost incurred at initial construction and every rehabilitation activity. This is estimated separately for each alternative using the life-cycle cost model. Note: LCC data is not yet available for the ABC projects. However, analyzing completed ABC projects and related literature, LCC are estimated. With a large number of projects being implemented while the performance data is being collected, LCC data estimates will be more precise. Mi-ABCD is a dynamic tool that can be updated with the availability of data.	*Correlation is dynamic. The alternative with the least cost will be directly correlated and the others will be inversely correlated.*	
		User cost	This considers the user cost incurred for initial construction of a bridge for each alternative. This is estimated separately for each alternative using the quantitative data input and available user cost models.	*Correlation is dynamic. The alternative with least cost will be directly correlated and the others will be inversely correlated.*	
		Economic impact on surrounding communities	This considers the region or county of the bridge project and estimates the impact on the respective economy based on its Michigan county multiplier (Montgomery Consulting, Inc.). When the impact is high, this parameter is assigned a high preference, and vice versa.	SPMT Move, SIBC, PBES	CC
	Alternative Specific Cost (Note: All SPMT move specific costs are added to obtain *total SPMT move specific cost*. Similarly, all SIBC specific costs are added to obtain *total SIBC specific cost*)	Specialty equipment/ contractor cost for SPMT move	The cost is estimated based on a specialty contractor's lump sum cost from completed SPMT move projects (FHWA 2015).	*Correlation is dynamic and depends on the total alternative specific cost for SPMT move and SIBC. This parameter gives preference to the alternative with the least alternative specific cost. The preference is calculated by obtaining the cost differential between total SPMT move specific cost and total SIBC specific cost. The preference rating of 1 is assigned to PBES and CC in order to maintain these two alternatives as neutral with respect to the alternative specific cost parameter.*	
		Mobilization cost for SPMT move	Total mobilization cost is calculated by estimating the total weight of the superstructure and estimating the number of SPMT axle lines required. Data from completed SPMT move projects is utilized.		
		Travel path preparation cost for SPMT move	The cost is calculated based on allowable bearing pressure, thickness of base preparation, distance of staging area or length of travel path, and SPMT axle loads.		
		Staging area preparation cost for SPMT move	The staging area base preparation cost is calculated from geotechnical data providing the allowable bearing pressure, size of the superstructure, SPMT axle loads and depth of required sub-base,.		

		Temporary structure cost for SPMT move	The temporary structure cost for supporting the superstructure at the staging area is estimated based on the total weight of the superstructure and the type of temporary supports.	
		Specialty contractor cost for SIBC	This parameter considers the specialty contractor cost for SIBC implementation (excluding equipment and accessories cost, and preparing and operating cost). The cost needs to be specified by the user.	
		Equipment & accessories cost for SIBC	The cost of equipment and accessories for a SIBC project includes slide system, hydraulic jacks and accessories, slide guides, rollers, etc. This cost is estimated based on lump sum cost from completed SIBC projects (FHWA 2015).	
		Preparing & operating cost for SIBC	This considers all the costs associated with slide operations and includes costs related preparing and monitoring slide systems and hydraulic systems.	
		Temporary structure cost for SIBC	This includes the total temporary structure cost and is estimated based on the total weight of the superstructure. The estimate is derived from cost analysis of all completed SIBC projects. In the cost analysis, consideration is also given to different methodologies used in the projects. For example, when new structure is used as the detour then temporary structure cost is estimated accordingly. Note: This parameter is considering how much the temporary structure will add to the initial construction cost; as the decision-making is being performed during the design phase.	
Seasonal Constraints and Project Schedule (SC&PS)		Construction duration (days)	The on-site construction duration of each alternative is considered. This also represents the duration of detour for respective alternative. The difference in the number of construction days among the alternatives is calculated using the Eq. below. The alternative with the highest difference is assigned the highest preference. $V(\%) = \frac{\lvert V_i - Max(V_{PBES}, V_{SPMT}, V_{SIBC}) \rvert}{Max(V_{PBES}, V_{SPMT}, V_{SIBC})} \times 100$	*Correlation is dynamic and is decided based on the percentage difference. The highest percentage difference represents the shortest construction duration. Thus, the alternative with highest percentage difference will be directly correlated and the others will be inversely correlated.*

Technical Feasibility and Risk (TF&R)		*None*			
Site Consider-ations (STE)	Site vicinity	Procuring distance of specialty equipment	This parameter refers to mobilization of SPMTs. Since SPMT move is listed under *Inversely Correlated*, higher rating is assigned to the longer mobilization distance makes SPMT move less preferable. In addition, procurement distance assists in calculating *Mobilization Cost* that is used in cost comparisons with the other project delivery alternatives.	SIBC, PBES, CC	SPMT Move
		Number of clustered bridge replacement projects	This considers the number of bridge replacement projects within a reasonable proximity that have the potential to be clustered for SPMT move implementation. Higher number of such projects leads to higher rating for SPMT move as it will distribute the mobilization cost among such projects.	SPMT Move	SIBC, PBES, CC
		Availability of staging area	This secondary-level sub-parameter considers three possibilities: (1) staging area is unavailable, (2) staging area is suitable for SPMT move at a distance and a move path exists, and (3) staging area alongside and parallel to existing bridge is available and suitable for SIBC.	*Correlation depends on the three possibilities considered. For case-1, both SPMT move and SIBC are rated low. In addition, the sub-parameter "Staging area and travel path" is rated low for SPMT move. For case-2, SPMT move is preferred and the sub-parameter "Staging area and travel path" is rated for SPMT move based on its secondary-level sub-parameters. For case-3, SPMT move is less preferred compared to SIBC, and the sub-parameter "Staging area and travel path" is rated for SIBC based on its secondary-level sub-parameters, except travel path related parameters.*	
	Staging area and travel path	Allowable ground bearing pressure	This is related to SPMT move implementation. When the allowable bearing pressure is sufficient, SPMT move preference is rated high. In addition, this parameter helps in calculating the cost of "preparing travel path" and "preparing staging area" related to SPMT move.	SPMT Move	SIBC, PBES, CC

		Travel path grade	This is related to SPMT move implementation. If the travel path grade is low, then the parameter will have high preference; consequently, SPMT move will have high preference.	SPMT Move	SIBC, PBES, CC
	Feature intersected (FI)	Significance of FI class (e.g., freeway, arterial, etc.)	This parameter considers the FI classification based on HCM and the respective underclearance requirements.	*Correlation is dynamic and depends on the FI class and the existing underclearance. SPMT move is more preferred if the FI is under National Highway System and underclearance is adequate. However, if FI is under local road then both SPMT move and SIBC are preferred. Only SIBC is preferred if FI is under local road and underclearance is not adequate (i.e., existing underclearance need to be increased). If the FI is a railroad and underclearance needs to be increased, SIBC is preferred.*	
Structure Consider-ations (STR)	Existing superstructure	Underclearance	This considers the requirement of increasing the underclearance based on current MDOT bridge design standards. The parameter's ordinal scale rating is calculated based on the FI class and the existing underclearance. For example, if the FI class is a freeway and the facility carried underclearance is less than 14.25 ft, the underclearance will be increased to 16.25 ft or more. In that case, this parameter will be assigned an ordinal scale rating of 9. Note: For the case that requires changing the alignment to increase the underclearance, SPMT move involves more complexity building constructing a structure in the staging area to meet the tolerances of the final alignment that is not yet constructed. The as-built elevation/ inclination at final alignment will be unknown at the time of building new structure in the staging area.	SIBC, PBES, CC	SPMT Move (Note: The user can choose SPMT move to be directly correlated if special jacking equipment is available for a project to accommodate raising or lowering the structure.)
		Vertical grade/ slope	This considers the complexity introduced due to extreme slope of the bridge. If the vertical grade/slope of the existing superstructure is low, the parameter will have high preference; consequently, PBES and CC will have high preference.	PBES, CC	SPMT Move, SIBC

	Existing substructure/ foundation	Reuse potential with or without improvements	This parameter considers the three cases: (1) existing substructure or foundation cannot be reused, (2) existing substructure or foundation can be reused with improvements, and (3) existing substructure or foundation is fully reusable. If case-1, then the secondary-level sub-parameters "Challenge level of constructing new foundation when bridge is in service" and "Challenge level of constructing new foundation when bridge is not in service" will be applicable. If case-2, then the retrofit can be performed by possibly diverting traffic onto new structure. If case-3, then the new superstructure can be replaced without substructure modification or construction.	*Correlation is dynamic and depends on the case. If case-1, the preference is decided based on the parameters:* "Challenge level of constructing new foundation when bridge is in service" and "Challenge level of constructing new foundation when bridge is not in service." *If case 2, SIBC is highly preferred. If case 3, SPMT move and PBES are highly preferred; however, SIBC preference will be low because the original substructure design would not have considered sliding forces.*	
	Span	New span length	This parameter identifies the possibility of increasing or maintaining the existing maximum span length for the new structure.	*Correlation is dynamic and depends on the existing maximum span and new maximum span values. If the new maximum span length is greater than existing maximum span length, SIBC is preferred. However, if the new maximum span length can be made similar to the existing maximum span length, SPMT move is preferred.*	
		Number of similar spans	This parameter considers that an increased number of similar spans allows the use of similar components thus economy of scale. This parameter prefers SPMT move and PBES implementations. Note that with a large number of spans, the travel path preparation and staging area preparation costs for SPMT move will be high; and, those parameters address the SPMT move viability with respect to cost.	SPMT Move, PBES	SIBC, CC

The project specific quantitative data is categorized into (i) site-specific data, (ii) traffic data, and (iii) cost data. Table 3–9, column 1, describes the data type; column 2 lists the parameters used in the scoping framework; column 3 describes the actions required to provide data or the data available categories to select from; and column 4 lists the data sources.

Table 3–10 is prepared for traffic data. This table format is similar to that of Table 3–9. Table 3–10 requires level-of-service (LOS) data for FC, FI, and the detour before and during construction. The LOS data needs to be available from a preliminary traffic study at the site. Table 3–11 is prepared for the cost data. The traffic data and cost data assist in calculating some cost parameters for the delivery alternatives. However, data from completed similar bridge projects is needed to complete all the costs required for the scoping process.

Table 3–9. Site-Specific Data

Data Description		Parameter(s)	Data Input Options		Data Source
County of the project site		Economic impact on surrounding communities	Select the appropriate county		Michigan multipliers
Availability of staging area		-do-	Unavailable		Past ABC projects (FHWA 2015)
			Staging area is at a distance and a move path exists – Suitable for SPMT move		
			Staging area is alongside and parallel to existing bridge - Suitable for SIBC		
Specialty equipment procuring distance		-do-	250 mi or less		SPMT equipment hub distances from Michigan
			250 – 500 mi		
			500 – 1000 mi		
			1000 – 1500 mi		
			More than 1500 mi		
Number of clustered bridge replacement projects		-do-	Classification: 1 to 4, or more than 4		UDOT ABC projects and others
Allowable ground bearing pressure		-do-	>8 k/ft^2		Sarens SPMT technical data & Web Soil Survey (USDA)
			>6 to <=8 k/ft^2		
			>4 to <=6 k/ft^2		
			>2 to <=4 k/ft^2		
			<=2 k/ft^2		
Travel path slope		-do-	Less than 4%		Web Soil Survey (USDA 2013)
			4-6%		
			6-8%		
			More than 8%		
Distance to staging area (or) move path length		Travel path preparation cost	[*Input required*](mi)		Project specific information
(i) Feature intersected (FI) class	**(ii)** Existing underclearance	Significance of FI class & Underclearance	**(i)** Freeway or NHS arterials	**(ii)** 14.25 ft or less	MDOT Bridge Design Manual (MDOT 2014a)
				Up to 15 ft	
				Up to 16.25 ft	
				More than 16.25 ft	
			Non NHS arterials, collectors, local roads	14 ft or less	
				Up to 14.5 ft	
				More than 14.5 ft	
			Railroad	Less than 23 ft	
Vertical grade/slope of the existing superstructure		-do-	4% or less		Ardani et al. 2009 (UDOT)
			4-6%		
			Up to 8%		
			More than 8%		
Reuse potential of existing substructure with or without improvements		-do-	Cannot be reused		Past ABC projects (FHWA 2015)
			Can be reused with repairs		
			Can be reused with minor upgrades		
(a) New span *(Input required)*	**(b)** Existing span *(Input required)*	-do-	**(a), (b)** New to existing span difference > 40 ft		UDOT SPMT projects& SHRP 2 R04 demonstrations ABC projects and others
			New to existing span difference = 21-40 ft		
			New to existing span difference = 10 - 20 ft		
			New to existing span difference < 10 ft		
			Existing max. span > New max. span		
Number of similar spans		-do-	Classification: 1 to 4, or more than 4		

Note: "-do-" is used when the parameter label and data description are the same.

Table 3–10. Traffic Data

Data Description	Parameter(s)	Data Input Options		Data Source
		Facility Carried	*Feature Intersected*	
ADT	User cost & Life-cycle cost	[*Input required*]	[*Input required*]	Bridge Management Database; Traffic Study
Speed limit (mph)		[*Input required*]	[*Input required*]	
Traffic directionality		[*Input required*]	[*Input required*]	
Number of lanes in each direction		[*Input required*]	[*Input required*]	
Work zone length (mi)		[*Input required*]	[*Input required*]	
Work zone speed limit (mph)		[*Input required*]	[*Input required*]	
Functional class		[*Select from HCM roadway classification*]	[*Select from HCM roadway classification*]	
Average queue length and its duration on FI due to work zone		[*Input required*]		
Detour availability	-do-	Unavailable		Project information
		Available		
Detour length (mi)	-do-	[*Input required*]		Traffic study
ADT on detour	User cost & Life-cycle cost	[*Input required*]		
Detour speed limit (mph)		[*Input required*]		
		LOS Data (Ranges from A to F)		
		Before Construction	*During construction with respect to each alternative (CC, PBES, SIBC, SPMT Move)*	
LOS on FC	-do-	[*Input required*]	[*Input required*]	Traffic Study
LOS on FI	-do-	[*Input required*]	[*Input required*]	
LOS on detour route	-do-	[*Input required*]	[*Input required*]	
LOS on nearby major intersection due to traffic on FC with full closure	Impact on nearby major intersection/ highway-rail grade crossing with full closure	[*Input required*]	[*Input required*]	
LOS on nearby major intersection due to FI traffic	Impact on nearby major intersection/highway-rail grade crossing due to FI traffic	[*Input required*]	[*Input required*]	

Note: "-do-" is used when the parameter label and data description are the same.

Table 3–11. Cost Data

Data Entry/Item	Parameter	Data Input	Remarks
Initial construction cost (excluding the specialty contractor cost)	Construction & Life-cycle cost	[*Input required*] (for each project delivery alternative)	Need to estimate using information from past projects
Maintenance of traffic (MOT)cost per day {mean value irrespective of the project delivery alternative}	Maintenance of traffic (MOT) cost	[*Input required*]	
Utility relocation cost	-do-	Calculated	Based on number of major utilities affected and level of difficulty for relocation
Number of years for life-cycle cost analysis	Life-cycle cost	[*Input required*] (for each project delivery alternative)	Life-cycle cost (LCC) is calculated. Parameters required for LCC calculation are estimated using data from similar bridge projects.
Cost per each maintenance/repair activity			
Average duration between maintenance activities			
Disposal or salvage value			
User cost	-do-	Calculated	Based on quantitative data entries
Specialty equipment/ contractor cost for SPMT move	-do-	Calculated	Based on the cost database developed from past SPMT move projects
New structure: **(a)** Width; **(b)** Length; **(c)** Max. span length; **(d)** No. of main spans	Mobilization cost for SPMT move & Temporary structures cost for SPMT move and SIBC	Calculated	Based on past SPMT move and SIBC project information
Travel path preparation cost for SPMT move	-do-	Calculated	Based on allowable bearing pressure, thickness of base preparation, length of travel path, size of the superstructure, and SPMT axle loads
Staging area preparation cost for SPMT move	-do-	Calculated	
Equipment & accessories + preparing & operating cost for SIBC	Equipment & accessories & Preparing & operating cost for SIBC	Calculated	Based on the cost database developed from past SIBC projects
Specialty contractor cost for SIBC (Note: If the general contractor is self-performing the SIBC operation, then this cost is included under "equipment & accessories + preparing & operating" cost)	-do-	[*Input required*]	Need to be estimated based on contractor availability and qualifications.
Construction duration (days)	-do-	[*Input required*] (for each project delivery alternative)	Need to be estimated based on past project information.

Note: "-do-" is used when the parameter label and data entry/item are the same.

3.4 QUALITATIVE DATA

The qualitative parameters are assigned an ordinal scale rating (i.e., from 1 to 9) based on the user experience from past projects. The qualitative parameters under each major-parameter are shown as a preference-rating questionnaire in Table 3–12. The users who assign the ratings are also expected to provide comments for their preferences.

To facilitate the users in deliberating the appropriate rating while providing preferences, the context to the preference-rating questionnaire is described and the questionnaire is grouped into: (1) site-specific preference ratings, and (2) alternative-specific preference ratings, as shown in Table 3–13. The site-specific preference ratings are assigned by users familiar with the project site, stakeholders, and surrounding communities. The alternative-specific preference ratings are assigned by users familiar with the project delivery alternatives and associated processes, and their applicability to the project site. Using the context provided in Table 3–13 and past project experiences, users can assign an unbiased preference rating for the alternative-specific parameters.

The qualitative parameters are correlated with the project delivery alternatives similar to quantitative parameters, as described in Table 3–13. The correlations are needed for the Mi-ABCD methodology to evaluate the alternatives. The definition of *Directly Correlated* and *Inversely Correlated* alternative(s) is provided in Section 3.3. The *Remarks* column in Table 3–13 provides additional information for each qualitative parameter that the user should be aware of while contemplating the appropriate preference rating.

Table 3–12. Qualitative Parameters and Associated Ordinal Preference Rating Scale

Major-Parameter	Sub-Parameter	Qualitative Parameter	Preference Rating Scale		User Comments
			1	9	
Work Zone Mobility (WZM)	Lane closure considerations	Closure of curb-lanes on the bridge	Not possible	Highly possible	Reasons behind the ratings
		Lane closure/traffic shift restrictions on feature intersected	Low	High	
Cost	Indirect Cost	Economic impact on surrounding businesses	Low	High	
Seasonal Constraints and Project Schedule (SC&PS)		Stakeholders limitations	Low	High	
		Seasonal limitations	Low	High	
Technical Feasibility and Risk (TF&R)	Risks	Financial and political (risk)	Low	High	
		Traffic within work zone on FI	Low	High	
	Contractor experience	Contractor/ Specialty contractor qualifications	Limited	Experienced	
		Manufacturer/ Precast plant experience	Limited	Experienced	
Site Considerations (STE)	Staging area and travel path	Impact on overhead and underground utilities	Low	High	
		Environmental sensitivity of staging area	Low	High	
		Travel path complexity	Low	High	
	Feature intersected (FI)	ROW availability on FI for equipment staging for PBES	Limited	Unrestricted	
	Limitations for SIBC	Available ROW for SIBC	Limited	Unrestricted	
		Site constraints for parallel replacement-structure construction	Minor	High	
		Site condition complexities [Terrain to traverse]	Not difficult	Difficult	
		Scour or hydraulic complexities	Low	High	
		Environmental protection near and within the site	Low	High	
		Aesthetic requirements	Low	High	
Structure Considerations (STR)	Existing superstructure	Impact on utilities on the structure	Low	High	
		Feasibility of staged construction	Not feasible	Feasible	
	Existing substructure/ foundation	Complexity of constructing new foundation when bridge is in service	Minimal	Extreme	
		Complexity of constructing new foundation when bridge is not in service	Low	High	
		Limitations for PBES construction	Low	High	
		Geometric complexity for SPMT move	Low	High	

Table 3–13. Qualitative Parameters' Preference Rating Questionnaire and Associated Context

<table>
<tr><th rowspan="2">Parameter</th><th rowspan="2">Preference Rating</th><th rowspan="2">Context</th><th colspan="2">Project Delivery Alternatives</th><th rowspan="2">Remarks</th></tr>
<tr><th>Directly Correlated to Preference Rating</th><th>Inversely Correlated to Preference Rating</th></tr>
<tr><td colspan="6">Site-Specific Preference Ratings</td></tr>
<tr><td rowspan="3">Closure of curb-lanes on the bridge</td><td>Not possible
(Range: 1)</td><td>Bridge configuration restricts closing any of the curb-lanes before the ABC window.</td><td>SPMT Move, SIBC</td><td>PBES, CC</td><td rowspan="3">This parameter considers the possibility of closing the curb-lanes of the bridge prior to the ABC window.

Note: ABC window is the time period that the entire FC is allowed to close in order to place the superstructure, and complete approaches, and other activities required to open the road to traffic.</td></tr>
<tr><td>Moderately possible
(Range: 2-5)</td><td>Only one of the curb-lanes can be closed or similar restriction that moderately constraints the SPMT move and SIBC preparation before the ABC window.</td><td colspan="2" rowspan="2">Example:
If there is a high possibility of closing both curb-lanes or shifting traffic by reducing the number of lanes, SPMT move and SIBC will have high preference. This is due to time and space availability to prepare the site and test the equipment/set up prior to the ABC window.</td></tr>
<tr><td>Highly possible
(Range: 6-9)</td><td>Existing bridge configuration allows closing both curb-lanes or shifting traffic by reducing the number of lanes to allow for conditions that will expedite SPMT move and SIBC preparation before the ABC window.</td></tr>
<tr><td rowspan="3">Lane closure/ traffic shift restrictions on feature intersected (FI)</td><td>Low
(Range: 1-2)</td><td>FI configuration allows closing at least one lane and traffic shifts before the ABC window.</td><td>SPMT Move</td><td>SIBC, PBES, CC</td><td rowspan="3">This parameter considers the restrictions on lane closure or traffic shifts on FI before the ABC window. In this case, the substructure construction affects the FI traffic more or less in a similar magnitude while implementing SPMT move, SIBC, PBES and CC. From the analysis of completed ABC projects, it is observed that while implementing SPMT move, the FI traffic is affected only during ABC window. Conversely, while implementing SIBC, PBES, and CC, the FI traffic encounters lane closures, narrowed lanes, traffic shifts or intermittent road closure during the superstructure construction.</td></tr>
<tr><td>Moderate
(Range: 3-6)</td><td>Only curb-lanes on FI can be closed before the ABC window.</td><td colspan="2" rowspan="2">Example:
If the lane closures or traffic shifts are restricted on FI before the ABC window, and full closure is only allowed for replacing the bridge superstructure, SPMT move is preferred. Consequently, SIBC, PBES, and CC is less preferred because of on-site construction activities that require lane closures, narrowed lanes, and/or traffic shifts on FI.</td></tr>
<tr><td>High
(Range: 7-9)</td><td>Lane closures and traffic shifts on FI are limited or highly restricted before the ABC window.</td></tr>
</table>

Economic impact on surrounding businesses	Low (Range: 1-2)	Impact of bridge construction to the surrounding businesses is minimal.	SPMT Move, SIBC	CC, PBES	This parameter considers the number of surrounding businesses or major stakeholders that are affected because of the bridge replacement project. Note: When the impact is high, SPMT move and SIBC are considered as the preferred project delivery alternatives.
	Moderate (Range: 3-6)	A few local businesses are affected.	*Example:* If a large number of businesses or a major stakeholder experiences difficulties because of the bridge replacement project, SPMT move and SIBC are preferred over CC and PBES.		
	High (Range: 7-9)	A large number of businesses or a major stakeholder is affected.			
Stakeholders limitations	Low (Range: 1-2)	No more than one stakeholder with flexible schedule can tolerate an extended construction window.	SPMT Move, SIBC	PBES, CC	This parameter considers the limitations imposed by the stakeholders on the construction window of a bridge rehabilitation or replacement project. Note: SIBC is inversely correlated to the preference rating if stakeholders' limitations are on FI Examples of stakeholders' limitations on FI are: limitations from a waterway or navigational channel or railroad authority, utility interruption restrictions from utility company, tourism or recreational location constraints, etc.
	Moderate (Range: 3-5)	Few stakeholders imposing limitations on the construction window, but can tolerate short delays.	*Example:* If there are many stakeholders or a major stakeholder with limited tolerance to short delays, the construction window is assumed to be constrained. Thus, SPMT move and SIBC are preferred. A few examples of such stakeholders include emergency care facilities, fire department, and schools.		
	High (Range: 6-9)	Many stakeholders or a major stakeholder with limited tolerance to short delays.			
Seasonal limitations	Low (Range: 1-2)	Project in a region with low probability of severe weather events that will impact the on-site construction schedule.	SPMT Move, SIBC, PBES	CC	This parameter considers the likely weather events that will impact the on-site construction schedule.
	Moderate (Range: 3-5)	Project in a region with moderate probability of severe weather events that will impact the on-site construction schedule.	*Example:* If there is a high probability of severe weather events that will impact on-site construction schedule and hinder on-time project delivery, SPMT move, SIBC, and PBES are preferred. Consequently, CC is not preferred.		
	High (Range: 6-9)	Project in a region with high probability of severe weather events that will impact the on-site construction schedule.			

Financial and political (risk)	Low (Range: 1-2)	The project is of minor financial risk and no political impact.	PBES, CC *Example:* PBES and CC are considered to be more reliable alternatives because the procedures have been refined over the years and can be implemented with fixed price/variable scope procurement method. Conversely, SPMT move and SIBC being new/innovative construction methods involve high uncertainty and risks, and increased cost.	SPMT Move, SIBC	This parameter considers the financial risk and political impact associated with a project. Note: For this parameter, the level of financial risk and political impact is correlated considering that the new/innovative construction methods present a higher risk as well cost more than PBES and CC. With high financial risk and high political impact, low cost and reliable project delivery alternatives are preferred. When SPMT move and/or SIBC can be implemented with comparable costs to CC and PBES, the user can select to update the correlations in the framework.
	Moderate (Range: 3-5)	Moderate risk to allocate increased cost of ABC and a moderately politically sensitive project.			
	High (Range: 6-9)	High risk to allocate increased ABC cost and a highly politically sensitive project.			
Traffic within work zone on FI (risk)	Low (Range: 1-2)	Limited volume of traffic on FI is affected by the work zone.	SPMT Move	SIBC, PBES, CC	This parameter considers impact on FI traffic due to bridge construction. It is assumed that the substructure construction affects the FI traffic more or less the same. Since superstructure construction for SIBC is similar to CC or use of PBES, only SPMT move is highly preferred when the FI traffic impact is high.
	Moderate (Range: 3-5)	Moderate volume of traffic on FI is affected by the work zone.			
	High (Range: 6-9)	Large volume of traffic on FI is affected by the work zone.			
Site condition complexities (Terrain to traverse)	Not difficult (Range: 1)	Feature intersected (FI) is a local low volume road.	CC, PBES *Example:* If an extremely difficult site condition such a deep valley is present, then CC techniques that are well developed to deal with such situations can be implemented. Similarly, incremental launching technique that mostly deals with PBES components can be implemented for such sites. Thus, higher preference is assigned for CC and PBES over other alternatives.	SPMT Move, SIBC	This parameter evaluates challenges with site conditions for access and deploying equipment or a specific construction technology.
	Moderately difficult (Range: 2-6)	Access below the bridge is moderately difficult because of grade or right-of-way.			
	Extremely difficult (Range: 7-9)	Access below the bridge is extremely difficult such as over rapids, a deep valley, environmentally sensitive area, congested roadway with multiple ramps, etc.			

Scour or hydraulic complexities	Low (Range: 1-2)	Project is not scour critical and the foundation construction requires minor or no special consideration.	CC, PBES	SIBC, SPMT Move	This parameter considers the complexity related to scour.
	Moderate (Range: 3-4)	Project is rated as scour critical and requires minor work due to terrain and water level at the foundation without the need of specialized equipment.	*Example:* For typical highway bridges, the FI does not include waterways that can accommodate barges. Thus, use of SPMT move is not possible at such sites with high scour or hydraulic complexities. In the presence of scour conditions, driving piles for temporary structures may compromise structural stability of the in service bridge. Hence, SIBC is ruled out. Once the piles are driven, the rest of the construction can be completed either using PBES or CC techniques. Even though there will be challenges to place cranes for bridge construction using PBES, CC and PBES are preferred for sites with scour or hydraulic complexities.		
	High (Range: 5-9)	Project is rated as scour critical. Construction will be complex while constructing cofferdams or sheet piling due to water level and terrain (may require specialized equipment).			
Environmental protection near and within the site	Low (Range: 1)	Site does not involve any environmental consideration or require environmental permits.	PBES	SPMT Move, SIBC, CC	This parameter considers the site conditions such as wet land, endangered species, natural vegetation, etc., that require environmental protection requiring environmental review or permits.
	Moderate (Range: 2-5)	Site requires limited environmental considerations and obtaining permits for those are not complex. Also, substructure construction has moderate impact on the environment near and within the site, while deploying equipment near the FC.	*Example:* If environmental protection requirements near and within the site is high, both substructure and superstructure construction can be performed by the equipment at the bridge approach or on the superstructure as the bridge construction proceeds. As an example, the PBES top-down approach can be implemented. SIBC implementation requires temporary substructure construction and additional area for superstructure construction on temporary supports. SPMT move implementation requires base preparation and access from below the superstructure. Hence, SIBC and		
	High (Range: 6-9)	Site requires significant environmental preservation near and within the limits of construction. Also requires environmental permits with complex applications.			

<table>
<tr><td></td><td></td><td>Also, substructure construction has high impact on the environment near and within the site, when performed by deploying equipment near the FC.</td><td colspan="2">SPMT move are not the preferred methods for such sites.</td><td></td></tr>
<tr><td rowspan="3">Aesthetic requirements</td><td>Low
(Range: 1)</td><td>Bridge carries a highway over a local route in a rural area.</td><td>CC, SPMT Move, SIBC</td><td>PBES</td><td rowspan="3">This parameter considers the location or region of the bridge, and associated cultural and historical significance. It is presumed that the architectural concepts are cheaper to implement in CC than PBES, and a bridge superstructure constructed on temporary supports for SPMT move and SIBC emulates CC. Also, CC can address the cultural and historical significance.</td></tr>
<tr><td>Moderate
(Range: 2-6)</td><td>Bridge is located in a rural area over an interstate highway or any similar situation that may require bridge or the view to be scenic.</td><td colspan="2" rowspan="2">Example:
Consider a bridge located in a touristic and dense urban area that requires addressing more aesthetic requirements for nearby structures; for such site CC, SPMT move, and SIBC is preferred; this is because, the superstructure construction for SPMT move and SIBC in staging area is equivalent to CC that allows more flexibility to incorporate aesthetic features during construction. Conversely, implementing PBES for such site may require unique formwork, and additional considerations for erecting and assembling the unique components; thus, PBES is the least preferred.</td></tr>
<tr><td>High
(Range: 7-9)</td><td>Bridge located in a touristic and dense urban area or at a site with cultural and historical significance that requires addressing aesthetics requirements.</td></tr>
<tr><td rowspan="3">Impact on utilities on the structure.</td><td>Low
(Range: 1-2)</td><td>None or one utility excluding pipelines.</td><td>SIBC, CC</td><td>SPMT Move, PBES</td><td rowspan="3">This parameter incorporates the complexity of relocating the utilities that are on the existing superstructure.

Note: The utilities may be attached on or below the superstructure. The most common utilities on bridges are telecommunication lines, power lines, and gas and water/sewer pipelines.</td></tr>
<tr><td>Moderate
(Range: 3-5)</td><td>Two to three utilities, and/or the relocation requires moderate effort.</td><td colspan="2" rowspan="2">Example:
The most complex situation arises when utility relocation is very challenging due to site constraints or significance of the utility. In such cases, the utilities are temporarily supported using false work; implementing CC or SIBC in these situations will be more preferred compared to SPMT move or PBES. The concern with SPMT move is that the move may interfere with the falsework supporting the utilities. Similarly, the presence of utilities and falsework may be a constraint for crane operations in PBES implementation.</td></tr>
<tr><td>High
(Range: 6-9)</td><td>More than three utilities, and/or the relocation requires significant effort.</td></tr>
</table>

Feasibility of staged construction	Not feasible (Range: 1)	Site conditions, existing structure geometry, existing structural system and condition, or a combination thereof restricts staged construction implementation.	PBES, CC, SIBC	SPMT Move	This parameter evaluates the feasibility of performing staged construction with the four project delivery alternatives listed here.
	Somewhat feasible (Range: 2-5)	Requires moderate work to address some of the above listed constraints.	*Example:* The traditional staged construction practice is the partial demolition of the existing bridge along a saw cut while the existing bridge still maintains traffic on a limited number of lanes. This practice has been widely used with CC and PBES. The traditional staged construction process can be emulated with SIBC without any difficulty. Another approach with SIBC is to have the FC traffic maintained on the new superstructure while the existing bridge is demolished, and foundations and substructure are reconstructed. Several staged construction methodologies for SIBC are documented in literature. Hence, CC, PBES, and SIBC are preferred. However, use of SPMT move for staged construction requires having staging areas on either side of the existing bridge or having access from either side of the structures. Hence, implementing SPMT move for staged construction is not preferred.		
	Feasible (Range: 6-9)	Requires minor work and can be implemented without any difficulty.			
Complexity of constructing new foundation when bridge is in service	Minimal (Range: 1-3)	Minimum or no complexity. As an example, the new bridge is on a new footprint, adequate headroom is available for foundation installation, and in service bridge safety is not compromised during foundation installation.	CC, PBES	SPMT Move, SIBC	This parameter considers the complexity of constructing new foundation when bridge is in service.
	Moderate (Range: 4-6)	Moderately complex situation. As an example, the new bridge is partially on the existing footprint;	*Example:* Typically, SPMT move is used to replace a bridge superstructure to minimize the FC		

<table>
<tr><td rowspan="2"></td><td></td><td>the existing bridge consists of a shallow foundation that is sensitive to construction activities, or requires ground stabilization before foundation construction.</td><td colspan="2" rowspan="2">closure duration. Hence, if foundation construction requires full-closure of the FC, use of SPMT move for such projects is not preferred.
SIBC requires construction of temporary structure adjacent to the existing bridge. SIBC is not preferred when the existing bridge foundations are sensitive to vibrations or require additional work to ensure stability of the in-service bridge.
When highly complex situations arise, the most common approach is to demolish the existing bridge and construct the foundation. In such cases, PBES can be used to expedite the construction or CC can be implemented. Hence, PBES and CC are the preferred project delivery alternatives when foundation construction is difficult while the existing bridge is in service.</td><td rowspan="2"></td></tr>
<tr><td>Extreme
(Range: 7-9)</td><td>Extremely complex situation.
As an example, the new bridge is on the same footprint with the existing bridge, low head room, requires driving piles near the existing foundation, the soil is sensitive to vibration, structural stability is of concern, or a combination of any of the conditions listed above.</td></tr>
<tr><td rowspan="3">Complexity of constructing new foundation when bridge is not in service</td><td>Low
(Range: 1)</td><td>No complexities for constructing new foundation following old bridge demolition.</td><td>SIBC</td><td>PBES, SPMT Move, CC</td><td rowspan="3">This parameter represents the complexity in constructing new foundation when the existing bridge is not in service (i.e., after demolition).</td></tr>
<tr><td>Moderate
(Range: 2-5)</td><td>Project involves certain site conditions that create moderate conditions that create moderate complexity and may require ground improvements.</td><td colspan="2" rowspan="2">Example:
The increase in complexity for constructing foundation after demolition of old bridge increases the impact on FC. In this case, implementing SIBC is more effective because the FC traffic can be accommodated via temporary run-around on new superstructure. However, implementing PBES, SPMT move, and CC will not be efficient under such conditions.</td></tr>
<tr><td>High
(Range: 6-9)</td><td>Project involves complexities such as extensive ground improvement, shallow water table, driving piles in difficult conditions, etc., that may require extended amount of time for constructing new foundation after bridge demolition.</td></tr>
</table>

Alternative-Specific Preference Ratings					
Contractor/ Specialty contractor qualifications	Limited (Range: 1-3)	Available contractor/specialty contractors have limited experience with the project delivery alternative under consideration.	The project delivery alternative considered for rating.	Rest of the project delivery alternatives.	This parameter considers the available contractors and their respective qualifications for a particular delivery alternative. This parameter needs to be rated independently with respect to SPMT move, SIBC, PBES, and CC.
	Moderately experienced (Range: 4-6)	Available contractor/specialty contractors have moderate experience with the project delivery alternative under consideration.	*Example:* PBES is rated high if there are several contractors experienced. Similarly, if a pool of experienced or qualified contractors and specialty contractors are available, the associated project delivery alternative (SPMT move or SIBC) is assigned a higher rating. The project delivery alternative with the highest rating becomes the preferred.		
	Experienced (Range: 7-9)	Available contractor/specialty contractors have sufficient experience with the project delivery alternative under consideration.			
Manufacturer/ Precast plant experience for PBES	Limited (Range: 1-2)	Manufacturer/precast plant have limited experience with PBES.	PBES	SPMT Move, SIBC, CC	This parameter considers the available manufacturers/precast plants within realistic reach of a bridge replacement project. The experience of manufacturer/precast plant needs to be rated envisioning PBES appropriateness and expected tolerances at the bridge replacement project.
	Moderately experienced (Range: 3-6)	Manufacturer/precast plant have moderate experience with PBES, and can manufacture components with the specified tolerances.	*Example:* If there are several experienced manufacturers/ precast plants within a reasonable distance from the site, PBES is assigned a higher rating. Conversely, if experienced manufacturers/ precast plants are unavailable, SPMT move, SIBC, and CC will be preferred. SPMT move and SIBC are considered because the superstructure can be constructed using conventional methods and moved or slid into final position.		
	Experienced (Range: 7-9)	Manufacturer/precast plant have demonstrated experience with PBES, and their manufacturing with specified tolerances.			
Impact on overhead and underground utilities at staging area and travel path for SPMT move	Low (Range: 1-2)	There are no utilities to deal with at the staging area and/or travel path.	SIBC, PBES, CC	SPMT move	This parameter considers the complexity related to relocating underground or overhead utilities from the staging area and/or travel path for SPMT move implementation.
	Moderate (Range: 3-6)	Site contains few utilities at the staging area and/or travel path that can be relocated with moderate cost and effort.	*Example:* If it is highly complex and expensive to relocate the overhead and underground utilities at the staging area, SPMT move is the least preferred.		

	High (Range: 7-9)	Site contains a major utility such as a pipeline or several overhead and/or underground utilities at the staging area and/or travel path. Protection/relocation of utilities is expensive and complex.			
Environmental sensitivity of staging area for SPMT move or PBES	Low (Range: 1)	Staging area does not require special attention.	SIBC, CC, PBES	SPMT Move	This parameter considers the environmental significance of the staging area required for SPMT move or PBES implementation. Use of PBES might be restricted by the area required for component staging. The user can select if the PBES implementation requires a staging area near the site. If it does, PBES will be inversely correlated with the preference rating.
	Moderate (Range: 2-5)	Staging area requires moderate attention but without the need for permits.	*Example:* This parameter is about the staging area. SPMT move implementation requires base preparation and construction of temporary supporting structures. In this case, for a staging area with high environmental sensitivity, SPMT move would not be preferred. Here, it is assumed that the PBES are transported to the site as the bridge is being built rather than staging in a nearby location. SIBC utilizes right-of-way and not a separate storage area. Hence, PBES, SIBC, and CC are listed as the preferred delivery alternatives.		
	High (Range: 6-9)	Staging area requires significant attention and environmental permits because of its landscape, vegetation, wildlife or historical value.			
Travel path complexity for SPMT move	Low (Range: 1-2)	Travel path requires minor preparation work such as placing steel plates, wooden planks, etc. for SPMT move.	PBES, SIBC, CC	SPMT Move	This parameter considers travel path complexity ranging from low to high, and rated from 1 to 9.
	Moderate (Range: 3-5)	Travel path requires base preparation or temporary earth fill to connect the staging area to a paved roadway or to accommodate high differential grade along travel path.	*Example:* When the travel path complexity for SPMT move is rated high, SPMT move becomes the least preferred alternative.		
	High (Range: 6-9)	Travel path requires extensive base preparation. It may also include a bridge for traversing, railway tracks, curved roadway, limited horizontal clearance or access, etc., making SPMT move extremely difficult to implement or impractical.			

Right-of-way (ROW) availability on feature intersected (FI) for equipment staging for PBES	Limited (Range: 1-2)	ROW is limited and additional ROW acquisition is difficult.	PBES	SPMT Move, SIBC, CC	This parameter considers the ROW of FI for PBES equipment staging and is rated from 1 to 9 based on the limited to unrestricted access.
	Moderate (Range: 3-6)	Limited ROW available and additional ROW acquisition (i.e., purchasing temporary easement) is possible.	*Example:* If unrestricted access is available within the ROW for equipment placement, PBES is preferred. Please note that this parameter considers only equipment staging for PBES. There may not be adequate space available to build the temporary structure for SIBC.		
	Unrestricted (Range: 7-9)	ROW available and no additional ROW acquisition is required.			
Available ROW for SIBC	Limited (Range: 1-2)	Limited ROW alongside the existing bridge and additional ROW acquisition is difficult.	SIBC,	PBES, SPMT Move, CC	This parameter considers the ROW alongside the existing bridge that can be used as staging area especially for SIBC. The available space can be used for PBES storage and equipment placement.
	Moderate (Range: 3-6)	Limited ROW available alongside the existing bridge and additional ROW acquisition (i.e., purchasing temporary easement) is possible.	*Example:* When the ROW alongside the existing bridge is unrestricted, SIBC as well as PBES are highly preferred.		
	Unrestricted (Range: 7-9)	Sufficient ROW is available alongside the existing bridge that can accommodate new superstructure construction.			
Site constraints for parallel replacement-structure construction	Minor (Range: 1-2)	Site constraints may include abutment slope, overhead electric lines, soil erosion potential, etc., that require some consideration for SIBC implementation.	PBES, SPMT Move, CC	SIBC	This parameter considers the site constraints that especially impact the construction of new superstructure on temporary supports for SIBC. Note: For site conditions where the underclearance is not adequate, a new superstructure can be built at a higher elevation on temporary supports and lowered during ABC window or once over the permanent supports.
	Moderate (Range: 3-5)	Site constraints such as underclearance for feature intersected (FI), slope of FI, etc., that might affect SIBC implementation. Yet, the constraints are manageable for SIBC implementation.	*Example:* If the site is highly constrained for building the new superstructure alongside the existing bridge, SIBC implementation is the least preferred. Alternatively, minor site constraints such as overhead electric lines at parallel staging area can be managed while constructing the new superstructure; thus, SIBC implementation is not hindered and will not be rated low.		
	High (Range: 6-9)	Substantial site constraints alongside the existing bridge such as a deep valley, difficult access for temporary structure construction, any site feature that interferes with			

		superstructure construction, or any situations that make SIBC implementation impractical.			
Limitations for PBES construction	Low (Range: 1)	No limitations for specialized materials availability, and shipping and handling PBES components.	SPMT Move, SIBC, CC	PBES	This parameter considers the availability of specialized materials required for PBES construction (e.g., hi-performance concrete used in closure pours), and restrictions in transporting and erecting PBES components of new superstructure.
	Moderate (Range: 2-5)	Moderate difficulty to obtain specialized materials for PBES construction and/or Moderate transportation and handling limitations because of size and weight, but can be managed.	*Example:* With complex transportation limitations due to weight and size, the parameter is rated high and the PBES preference decreases. However, if the proposed superstructure has lightweight components, the parameter is rated low. Consequently, PBES is preferred.		
	High (Range: 6-9)	High difficulty to obtain specialized materials for PBES construction and/or Site is located in urban area with complex transportation limitations due to weight and size; requires permits or limits daytime access.			
Geometric complexity for SPMT move	Low (Range: 1-2)	Site layout including a typical highway bridge with standard configuration that can accommodate SPMT move with minor improvements to travel path	PBES, SIBC, CC	SPMT Move	This parameter considers the geometric features that prevent SPMT move implementation.
	Moderate (Range: 3-5)	Site layout requires moderate improvements and temporary earth fill to enable SPMT move.	*Example:* When several of geometric features that deter SPMT move operation are present at a site, SPMT move is rated low. Consequently, PBES, SIBC, and CC are rated high.		
	High (Range: 6-9)	Site layout includes ramps, extreme skew, embankment terrain, etc., that mostly deter SPMT move operation. Thus, it's highly difficult or impractical to implement SPMT move.			

3.5 PROJECT DELIVERY ALTERNATIVES COMPARISON METHODOLOGY

Project scoping framework for comparing CC and ABC project delivery alternatives were developed during the first phase of this project (Aktan and Attanayake 2013). In the earlier framework, ABC mainly reflected PBES project delivery alternative. The framework was the basis in the multi-criteria decision-making process as part of bridge project scoping to identify the optimal project delivery alternative. With the introduction of SPMT move and SIBC, two other accelerated project delivery alternatives, the project scoping framework is updated to compare four alternatives (CC, PBES, SPMT move, and SIBC). The expanded framework was presented in Section 3.2.

The project-scoping framework was customized for implementation in Michigan and supplemented with a guided software program titled Michigan Accelerated Bridge Construction Decision-Making (Mi-ABCD) tool. The expanded project-scoping framework needs to be integrated into the multi-criteria decision-making process, and the software program, Mi-ABCD, will be the continuation of this project.

3.5.1 Recommended Process for Expanding Mi-ABCD

In order to expand the decision-making process and the software program, Mi-ABCD, the following steps need to be completed:

1) Incorporate the new set of parameters discussed in Section 3.2 for scoping a project for CC, PBES, SPMT move, and SIBC project delivery alternatives.
2) Incorporate the project specific data tables discussed in Section 3.3.
3) Relate the quantitative parameters to data input ranges so that OSRs for the quantitative parameters can be developed. To accomplish this step, the site-specific data (Table 3–9) needs to be included with potential inputs, incorporated in the Mi-ABCD process using pull-down menus, and referenced to the *general data* in Mi-ABCD. The traffic data (Table 3–10) and cost data (Table 3–11) inputs need to be associated with mathematical models in Mi-ABCD to calculate: (i) costs specific to project delivery alternatives including user cost and life-cycle cost (discussed in Chapter 5), and (ii) impact on the affected roadways based on LOS. Next, the data ranges of the calculated costs need to be referenced to the *general data* in Mi-ABCD.

4) The qualitative parameters list needs to be updated including the preference rating benchmarks (i.e., context), as described in Section 3.4, in order to enable the users to enter preferences based on their experiences from completed projects.
5) Enhance the OSRs benchmarks by modifying the *general data* tables and cost calculations in Mi-ABCD, so that the aforementioned project specific data pertaining to new set of scoping parameters is referenced appropriately.
6) Correlate the parameters' OSRs with the project delivery alternatives based on the correlations presented in Table 3–8 and Table 3–13, in order to develop PCRs.
7) Update the AHP synthesis process in Mi-ABCD to incorporate CC, PBES, SPMT move, and SIBC alternatives based on the above PCR development process.
8) Update the output and preference-probabilities calculation in Mi-ABCD in order to incorporate the CC, PBES, SPMT move, and SIBC alternatives for comparison in groups or pairs.

In addition, while updating the Mi-ABCD, the existing Mi-ABCD concept of **Advanced User** and **Basic User** modules used in the earlier version needs to be enhanced. The **Advanced User** is the user who is most knowledgeable with all aspects of the project being scoped; whereas, the **Basic Users** are those who can provide insight in the scoping process based on their experience in earlier completed projects. In that notion, that **Advanced User** needs to be allowed to enter/edit all the data including: (1) scoping parameters discussed in Section 3.2, (2) site-specific data, traffic data, and life-cycle cost data as discussed in Section 3.3, (3) preference ratings for qualitative parameters as discussed in Section 3.4, and (4) *general data* that is reference to quantitative parameters. On the other hand, the **Basic Users** need to be allowed to enter/ edit preference ratings for qualitative parameters based on the context discussed in Section 3.4. Both **Advanced User** and **Basic Users** need to be able to access basic project information and access the evaluation results.

The alternative comparison results (output) can be presented in any or all of the following formats:

- Pie charts that show the upper and lower bound results of the user input: This helps in demonstrating the variability of the preference ratings assigned by the users.

- Line charts that show the distribution of major-parameter user preferences: This helps in providing the statistics of the normalized preferences for the major scoping parameters from the users. This information will be helpful in identifying the parameters that may indicate significantly different opinions from the users, and can be put forth among them for further review.
- Bar chart of Preference Probabilities for each user: This represents the preference probabilities of the project delivery alternatives from the users.
- Tabular format of Preference Probabilities Bar Chart: The data represented in bar charts can be presented in a tabular format for the users to itemize the preference probability distribution. From this, the contribution of the parameters' normalized preferences to the preference probabilities of the project delivery alternatives can be perceived and will be helpful in identifying the parameters with greater influence towards the final decision.

3.5.2 Process for Evaluating Limited Number of Alternatives

Two, three, or four alternatives among CC, PBES, SPMT move, and SIBC can be compared with expanded Mi-ABCD as discussed in the previous section. In this case, the data required will be the traffic and cost related to the alternatives that are being compared. For the site-specific data, the lowest range/value from the predefined list of potential inputs in Table 3–9 needs to be entered for each data item related to the alternative(s) not being compared. For the qualitative parameters, the user needs to assign an OSR "1" to those parameters related to alternative(s) not being compared.

The output calculation and display in the expanded Mi-ABCD need to be enhanced so as to consider only the alternatives that the user identifies for comparison. This can be achieved by modifying the distribution process of normalized preference ratings in Mi-ABCD, so that only the decision-making parameters related to the project delivery alternatives are included. The process can ultimately deliver the normalized preference ratings for the decision-making parameters and preference-probabilities for the project delivery alternatives under consideration.

When the users elect to compare only two or three alternatives, then the change in output will be represented in the bar chart and the tabular form. In this case, the preference probability distribution will be for only the alternatives being compared.

3.5.3 Process for Evaluating Pairs of Alternatives

The users can also elect to compare only two project delivery alternative groups (first set) with another (second set) among CC, PBES, SPMT move, and SIBC alternatives. In this case, the procedures will be similar to comparing all four alternatives; except to interpret the results, users need to utilize the tabular format output. Obtaining the itemized preference probability distribution from the tabular output, the users can identify the preference probabilities for the first set and second set independently, and then compare the preference probabilities of both sets for a final answer.

3.6 SUMMARY

The methodology in Mi-ABCD tool is considered and the scoping evaluation process is expanded to include Self-Propelled Modular Transporters (SPMT) move and Slide-In Bridge Construction (SIBC) project delivery alternatives along with Conventional Construction (CC) and Prefabricated Bridge Elements and Systems (PBES). A new set of scoping parameters are identified and synthesized into quantitative and qualitative classification. These parameters are an advancement to those used in the Mi-ABCD tool that compared only CC and general ABC process, especially PBES (Aktan and Attanayake 2013).

The project specific data pertaining to quantitative parameters include additional parameters specific to SPMT move and SIBC along with CC and PBES alternatives. The project specific data is categorized as: (1) site-specific, (2) traffic, and (3) cost. Site-specific data items are grouped into ranges to allow the user with pull-down menus for data input. The grouping into multiple ranges is based on specific bridge design criteria and experience extracted from earlier ABC projects. The traffic data can be entered from available sources; whereas, the cost data related to SIBC and SPMT move activities are obtained from unit costs calculated from completed ABC projects. The traffic and cost data are used in calculating the level-of-service (LOS) of the affected roadways and costs incurred from implementing a particular alternative. Several additional costs associated with SPMT move and SIBC alternatives are also considered, and the user cost and life-cycle cost methodologies are updated.

The qualitative parameters are incorporated by implementing Ordinal Scale Ratings (OSRs) that the users enter by assigning preference rating on an ordinal scale of 1 to 9. In addition, *context* for each qualitative parameter is explained, and scenarios for situations are described for supporting the rating process. The *context* for each qualitative parameter is grouped into ranges of OSRs associated with level of preferences. The qualitative parameters for preference ratings are grouped under (1) site-specific and (2) alternative-specific.

Comparing project delivery alternatives, the quantitative parameters and qualitative parameters are defined as *directly* or *inversely* correlated to the project delivery alternatives. For most of the quantitative parameters, the correlations are kept dynamic and are decided based on the project specific and values calculated for the quantitative data. For a few of the qualitative parameters that require preferring specific alternatives when specific conditions are met, the correlations are also kept dynamic. Besides the parameters with dynamic correlations, all others are defined as either directly or inversely correlated. The users have the option to modify the presets during the scoping process.

The scoping framework can be developed into a multi-user platform that will allow compiling input from multiple users and generating combined output. The Mi-ABCD tool developed during the previous phase of this project can be expanded to include comparison of CC, PBES, SIBC, and SPMT move project delivery alternatives. The site-specific, traffic, and cost data (as well as site-specific and alternative-specific preference ratings) require implementing additional worksheets into the Mi-ABCD tool. Furthermore, the enhancements need to include updating: (i) the correlations of parameters with the project delivery alternatives, (ii) Analytical Hierarchy Process (AHP) synthesis, and (iii) output and preference-probability calculations for the project delivery alternatives. The cost data estimation methodology presented in Table 3–11-*Remarks* column reduces the user input requirements by calculating the cost from the data compiled from completed projects. Cost calculations in Mi-ABCD tool need to be expanded to include additional costs (discussed in Chapter 5) for SIBC and SPMT move alternatives. The expanded Mi-ABCD tool can maintain consistency in the comparisons within project delivery alternatives with the use of advanced computing methodology. With the expanded tool, the users will be able to compare two, three, four or any subset of alternatives among CC, PBES, SIBC, and SPMT move.

4 FOUNDATION DESIGN, CONSTRUCTION, AND UPGRADE METHODOLOGIES WHILE A BRIDGE IS IN SERVICE

4.1 OVERVIEW

The primary objective of implementing ABC is to perform highway construction better, faster, cheaper, safer, and smarter. In fulfilling those objectives, one of the tasks of this project is to identify methodologies for foundation construction while the existing bridge is in service. Chapter 2's Literature Review presents (a) typical foundation types and advantages and limitations with respect to their implementations in ABC, (b) foundations implemented in ABC projects, (c) a summary of the foundation policies implemented by a number of selected highway agencies, and (d) a summary of foundations implemented in ABC and other projects as well as implementation successes and challenges. Case studies that are applicable to substructure construction are presented in Appendix A. Utilizing literature review results, this chapter presents a methodology to evaluate the potential for foundation reuse or replacement while the existing bridge is in service. When constructing foundations, while the existing bridge is in service, the impact of pile installation on the existing bridge's stability needs to be considered. Hence, a classification of foundation types, based on the degree of disturbance to the surrounding soil during foundation installation is described. Several factors need to be considered when specifying a foundation type for a particular site. These factors include soil condition, the impact of pile installation on the in-service bridge stability, ground improvement procedures, space considerations for equipment deployment and operation, risks associated with construction of specific foundation types, and associated risk mitigation strategies. These factors are incorporated into the methodology presented for foundation construction while the existing bridge is in service.

4.2 FOUNDATION TYPES AND CLASSIFICATION

Foundation can be classified with shape and size, construction method, or structural prospective. In this report, the displacement classification method is discussed since the objective is to identify methodologies for foundation construction while the existing bridge is in service. Figure 4-1 shows the displacement-based classification of foundations. Parameters such as the amount of displaced soil within the vicinity of the constructed foundation and the equipment used have a significant impact when the foundation is built in proximity to a structure. Projects often include constraints that control the foundation alternative selection such as time, accessibility, resources, cost, and design. The dynamic effect of installing a new foundation adjacent to an in-service bridge is also a consideration in ABC projects. The volume of displaced soil is a reasonable representation when evaluating the dynamic effects. The impact of the volume of soil displaced by the foundation type is classified in Figure 4-1. Foundation types highlighted in green are the most preferred for installing near an existing foundation while the existing bridge is in service. Foundation types highlighted in yellow require consideration based on the distance to the existing bridge foundation due to vibration concerns, reduced confinement of nearby foundations, or expertise needed to assure quality of the installed piles and stability of the in-service bridge. The foundation types highlighted in red are not suitable near the foundations of in-service bridges.

Another consideration in foundation construction near the existing bridge is the headroom. As shown in the case studies presented in Appendix A, shallow foundations, micropiles, and drilled shafts have been installed in highly constrained spaces. Out from these three types, driven micropiles can generate small amplitude vibrations. If the existing foundation is sensitive to such vibrations, cast-in-place micropiles can be used. Considering the commonly used foundation types, vibration due to pile installation, and the potential for use with limited headroom, shallow foundations, drilled shafts with supported excavations, and micropiles are recommended.

Sometimes, the construction quality of the drilled shaft can be a concern. Among the case studies reviewed, construction quality issues of drilled shafts with unsupported excavations are reported. Supported excavation for drilled shafts can assure the stability of the in-service bridge as well as foundation construction quality. Also, crosshole sonic logging (CSL) can identify concrete consolidation problems with drilled shafts. Technologies such as compaction grouting and jet grouting have been successfully used to remedy drilled shaft construction flaws.

Micropile cross-sectional areas are smaller compared to other deep foundation systems. Hence, buckling and lateral load capacities are concerns. Case studies presented in Appendix A include vertical and battered micropile groups to enhance the lateral load capacity. The buckling strength of micropiles can be enhanced by increasing steel casing thickness.

H-pile is preferred in Michigan. Vibration during driving is a parameter related to this pile type. With adequate headroom, H-piles can be installed at some distance from the in-service bridge supports. Under limited headroom, if justified with traffic closures during nights or weekends, other alternatives such as driving piles through the bridge deck can be considered. Zekkos et al. (2013) developed a tool to estimate ground virbration due to pile driving. This tool has been verified for a limited number of soil types. Even with limitations, such tools need to be utilized to predetermine the potential dynamic effects for planning purposes. During foundation installation, the existing bridge response needs to be monitored to assure its stability.

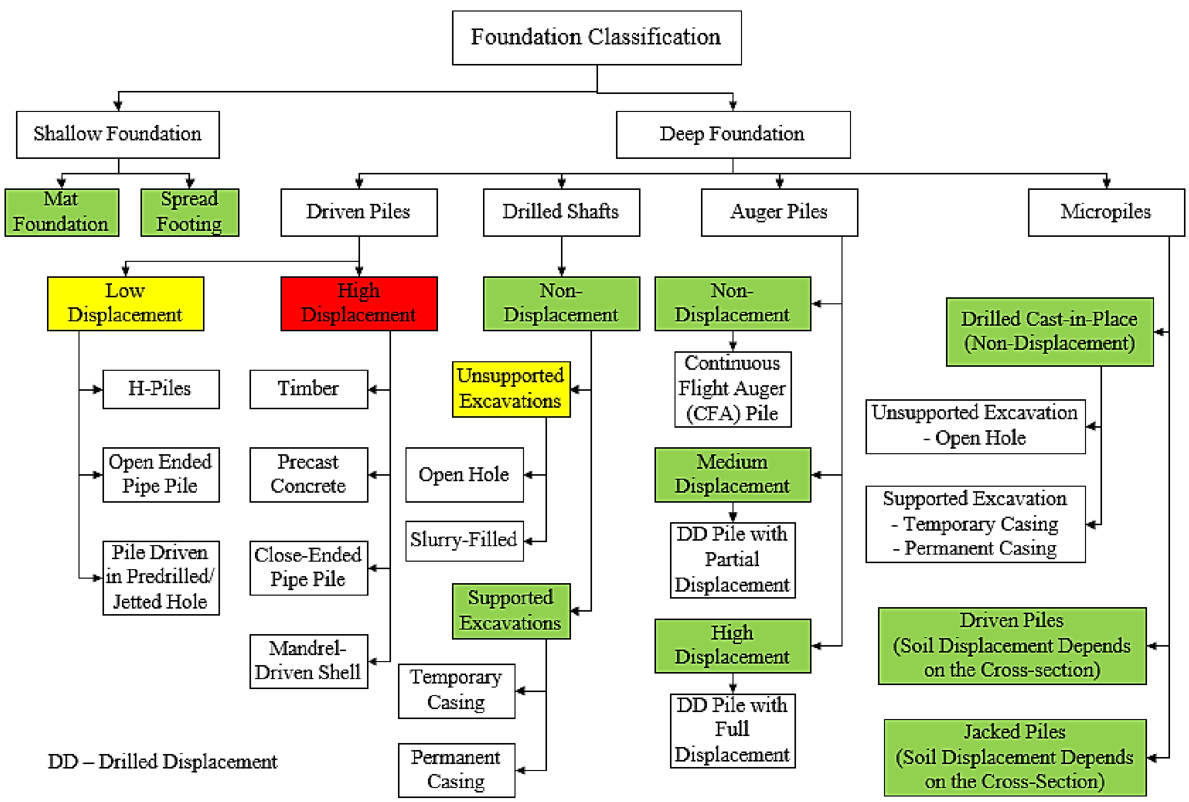


Figure 4-1. Foundation classification

4.3 SCOPING FOR FOUNDATION REUSE OR REPLACEMENT

Figure 4-2 shows a process for evaluating existing foundation reuse potential with or without retrofitting or need for replacement. The process requires the existing bridge and site data as well as the preliminary design of the proposed bridge. The next step is to establish if the new bridge footprint is on the same or partially on the same footprint of the existing bridge, or on a new footprint. If the new bridge is on the same or partially on the same footprint, foundation reuse potential or replacement can be evaluated. With the new bridge is on a different footprint, foundation and substructure alternatives can be evaluated for the feasibility of construction while the bridge is in service.

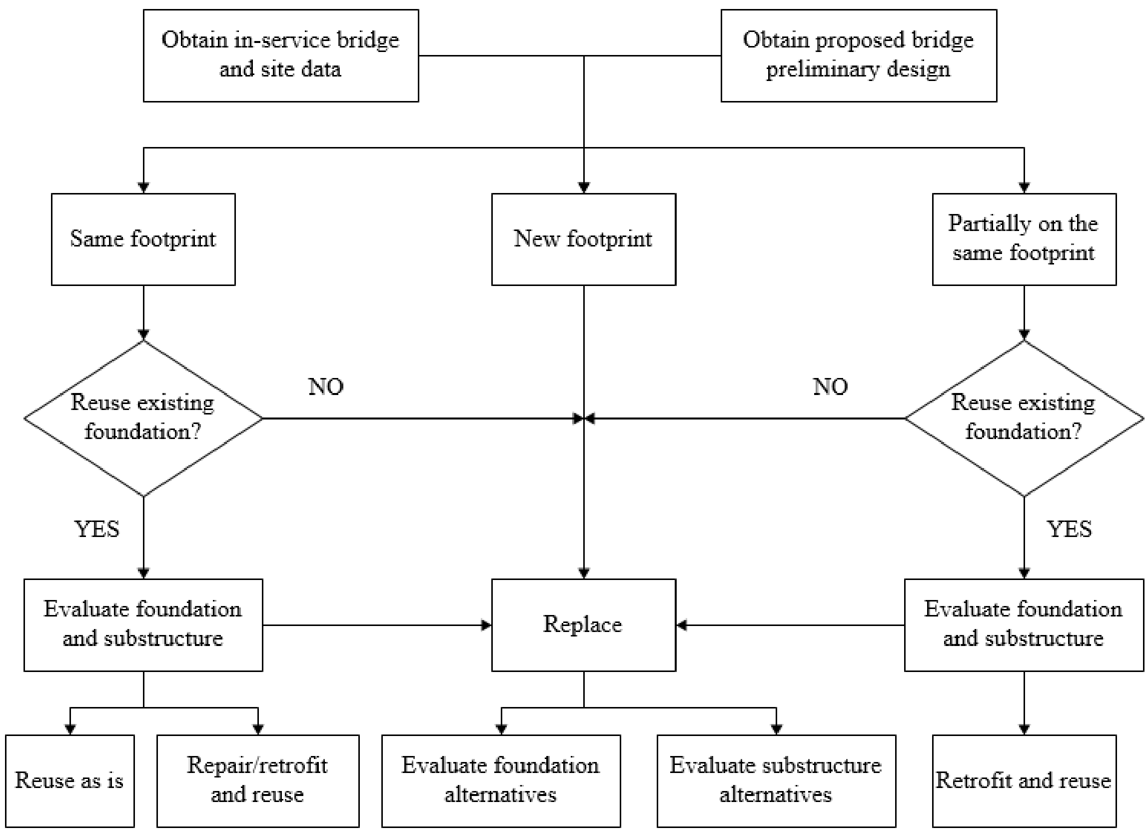


Figure 4-2. Scoping for foundation reuse or replacement while a bridge is in service

4.3.1 Foundation Reuse

The building and bridge communities recently have the tendency to evaluate the potential for foundation reuse before a replacement decision. As an example, Strauss et al. (2007) presents eight drivers for foundation reuse in the building industry. Drivers are location, archeology and historical constraints, geological conditions and constraints, sustainability and materials reuse, land value and cash flow projections, construction costs, consistency in the location of the structure, and approvals and development risks. The interest in reusing foundations in the building industry is due to difficulties and associated risks in constructing new foundations in congested urban areas. The complexities include the existing deep foundations at the site, underground infrastructure such as subway lines, and utilities. The bridge community also faces similar difficulties with bridge construction in urban areas. The foundation reuse decision heavily depends on the availability of good quality design and construction records as well as the current condition of the foundation. In other words, foundation reuse decisions are made based on the level of risk. When the condition of the existing foundation cannot be accurately determined, new foundations are incorporated to supplement the foundation capacity. With unknown foundation capacities, the reuse is highly unlikely.

In 2013, FHWA conducted a workshop on "foundation characterization" (Schaefer and Jalinoos 2013). The workshop was originally organized to discuss issues related to unknown foundations, and later the scope was broadened to cover condition evaluation of foundations. Foundation load capacity depends mainly on two factors: (1) the structural condition of the foundation and (2) the subgrade (soil profile and associated data). The following information is needed to assess the structural capacity of a foundation (Olson et al. 1998):

1. *Foundation Depth - bottom of the footing, pile, or combined system;*
2. *Foundation Type - shallow (footings), deep (piles or shafts), or a combination;*
3. *Foundation Geometry - buried substructure dimensions, pile locations;*
4. *Foundation Materials - steel, timber, concrete, or masonry;*
5. *Foundation Integrity - corroded steel, rotted timber, cracked concrete, etc.*

As shown in Figure 4-3, even when original documentation is available, data validation is essential to assure that the foundation design capacity has been preserved. On the other hand, assessment of an unknown foundation requires a detailed investigation to collect the necessary data. In order to collect reliable and sufficient data for the structural capacity assessment of a foundation, a testing program needs to be developed. The testing program may include a combination of visual, destructive, and non-destructive methods. Several non-destructive testing methods are available to evaluate the depth of an unknown foundation and

foundation integrity. These technologies are presented in the Federal Lands Highway Program, and can be accessed from:
http://www.cflhd.gov/resources/agm/engApplications/BridgeSystemSubstructure/index.cfm.
The necessary geotechnical data for load bearing capacity assessment can be collected from the original design or by a new geotechnical investigation.

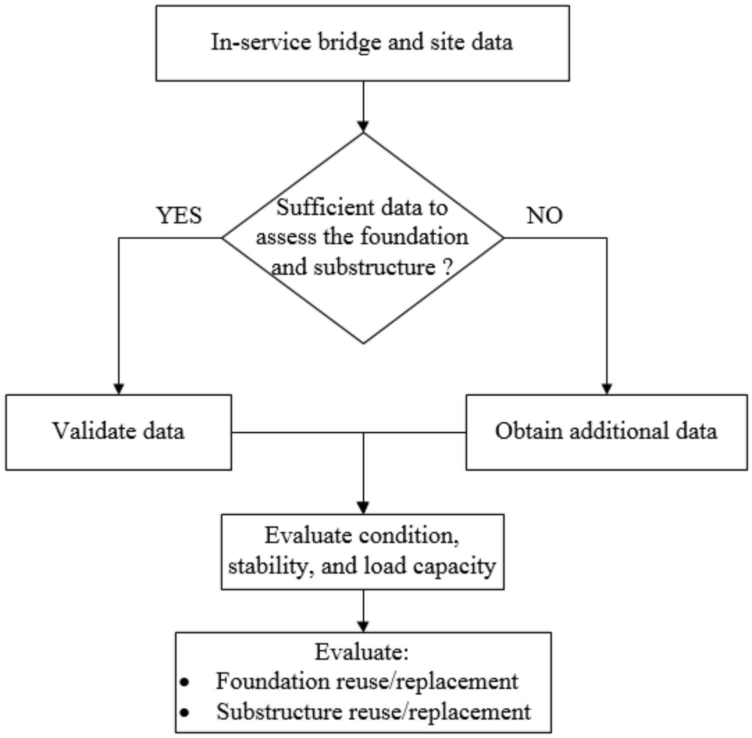


Figure 4-3. Substructure and foundation assessment process

In 2014, the FHWA conducted a second workshop with the focus on reusing foundations (Collin and Jalinoos 2014). While the European work documented in Strauss et al. (2007) and Chapman et al. (2007) is mainly focused on the building industry, the focus of the FHWA workshop is on the bridge foundation reuse. According to (Collin and Jalinoos 2014), the following are the drivers for bridge foundation reuse:

- ***Asset management***: *Existing foundations are assets with a functional value.*
- ***Technical drivers:*** *Replacing piles may be difficult.*
- ***Time savings***: *Reusing would minimize impacts on mobility.*
- ***Economic drivers***: *Reusing would lead to direct and indirect cost savings.*
- ***Efficiency***: *Reusing is a viable option for replacing structurally deficient superstructures.*

- ***Past performance**: The foundation must have performed adequately in the past; i.e., it has been load tested.*
- ***Environmental benefits**: Reusing would have a more limited impact on the environment.*
- ***Sustainability issues**: Reusing would save resources.*
- ***Historic preservation considerations**: Existing foundations would be better suited for structures with historical value.*

Collin and Jalinoos (2014) presented the extent of foundation reuse by surveying a limited number of DOTs (Table 4-1). As shown in the table, a majority has reused existing foundations as well as improved or fixed them to mitigate additional loads. However, the listed state DOTs did not indicate that they have policies or guidelines for evaluating existing foundations.

Table 4-1. Foundation Reuse by State Department of Transportations

State DOT	Has your State reused existing foundations for bridge replacement?	Has your State improved or fixed existing bridge foundations to mitigate for additional load (scour, seismic activity, etc.)?	Are policies and guidelines available to evaluate existing foundations?
ALDOT	No	Yes	No
CDOT	Yes	No	No
Caltrans	No	Yes	No
INDOT	No	Yes	No
KYTC	Yes	Yes	No
MnDOT	Yes	Yes	No
NYSDOT	Yes	Yes	No
NCDOT	Yes	Yes	No
TDOT	Yes	Yes	No
UDOT	Yes	No	No

Not included in Table 4-1, Illinois DOT has develop a comprehensive procedure and guidelines for foundation reuses (IDOT 2011). According to IDOT (2011), the exiting substructure and foundation elements are assumed to have adequate load capacity for reuse without a detailed structural analysis when the conditions listed below are satisfied:

- *The substructure elements are in good condition (NBI condition rating of 6 or greater), and show no significant structural distress under existing live load.*
- *The proposed service dead load is not greater than 115% of the original design service dead load.*
- *There is no significant reconfiguration of loads (i.e. no changes to bearing locations or substructure fixities.)*

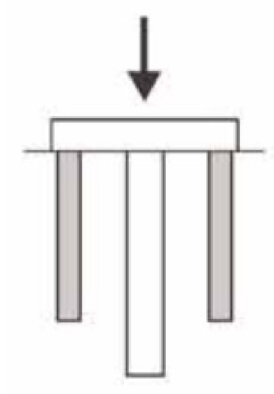
A detailed analysis is required to evaluate the reuse potential if the conditions are not met. The procedure with examples is described in IDOT (2011).

Foundation reuse gets complicated with unknown foundations. To accommodate future potential reuse, DOTs need to devise programs to document bridges with unknown foundations. As an example, the North Carolina Department of Transportation (NCDOT) developed a program in 2005. By November 2012, NCDOT completed documenting all the unknown bridge foundations (Schaefer and Jalinoos 2013).

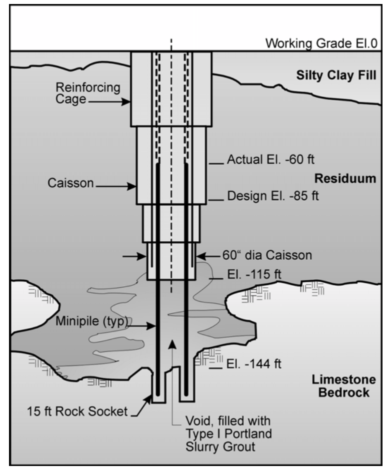
Among the large number of ABC projects reviewed, there were several cases with foundations constructed while the bridge was in service. None of the projects reused the existing foundations in most cases because the new bridge footprints were different than the existing bridges. Illinois DOT guidelines and procedures with the process depicted in Figure 4-3 can be considered for foundation reuse. Further studies are also required to comprehensively evaluate these procedures and refine available guidelines.

According to the flowchart shown in Figure 4-2, even when the new and existing bridge have the same footprint, reuse may need to be supplemented by a new foundation. Similarly, when the new bridge is partially on the existing bridge footprint, foundation retrofit may be required. Considering the case studies documented in Appendix A and recommendations in several publications, potential methodologies for enhancing existing foundation capacity are developed and presented in Figure 4-4. When the existing foundation is not suitable for reuse, the new foundations can be constructed in its vicinity by utilizing the load capacity of only the new foundation (Figure 4-5). As an example, Oregon constructed an 8 ft diameter drilled shaft next to the existing footing for the Route 38 at Milepost 39.64 over Elk Creek (Crossing No. 3) bridge replacement project. The drilled shaft was constructed while the existing bridge was in service. Later, the existing footing was abandoned, and the new structure was supported on the drilled shaft.

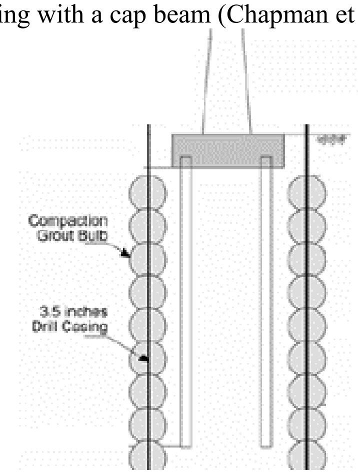
In Michigan, bridge foundations are not designed for large horizontal loads. However, ABC implementations such as SIBC can develop large horizontal forces during the slide due to pull or push mechanisms. Hence, it is essential to evaluate the capacity of the existing foundation to accommodate such forces. When the foundation lacks the required lateral load capacity, temporary bracings can be designed to support the substructure and foundations.



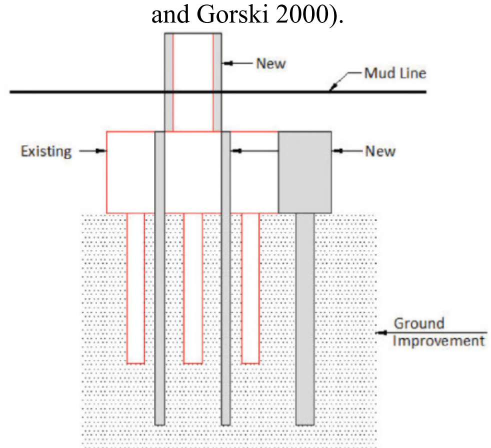
(a) Supplement the old foundation by installing new foundations outside the existing foundation and connecting with a cap beam (Chapman et al. 2007).



(b) Supplement the old foundation by installing micropiles within the existing foundation (Boehm and Gorski 2000).



(c) Compaction grouting to provide adequate confinement (Boehm and Gorski 2000).



(d) Supplement the old foundation by combining alternatives (Collin and Jalinoos 2014).

Figure 4-4. Retrofit methodologies for enhancing foundation capacity

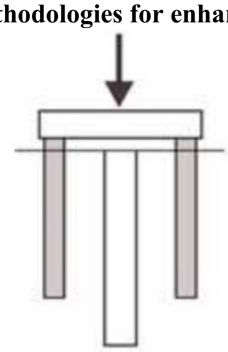


Figure 4-5. Install new foundations avoiding old foundations and transfer structural loads to the new foundation (Chapman et al. 2007).

A practical requirement of ABC, especially for SIBC and SPMT moves, is to construct foundations while the existing bridge is in service. Construction of the new foundation in the proximity of the existing foundation may compromise the stability of the in-service bridge. The use of shallow foundations, or non-displacement or low-displacement deep foundations wherever possible, is recommended. Further, supported excavation is recommended to assure the structural stability of the in-service bridge.

4.3.2 Construction of New Foundations

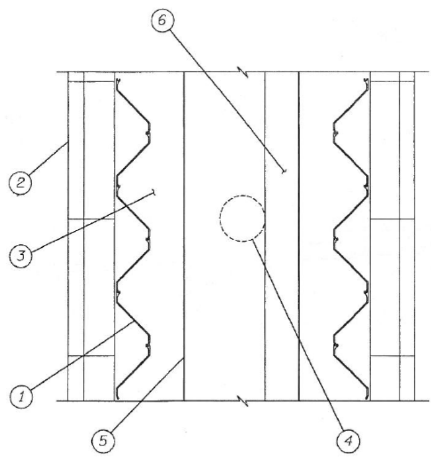
On the flowchart shown in Figure 4-2, the replacement bridge on a new footprint represents the majority of the ABC projects documented in Appendix A. The considerations for new abutment and pier construction within the vicinity of the existing bridge are discussed below:

4.3.2.1 Abutment Foundation

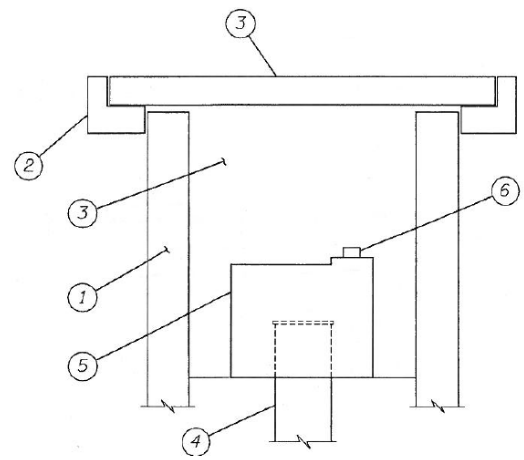
The new abutment can be constructed in front of the existing abutment. One such example is shown in Figure 4-6. Space required for abutment construction was acquired by excavating in front of the existing abutment. In order to assure the stability of the slopes and the bridge, temporary soil nail walls were used.

Figure 4-6. New abutment construction (Photo courtesy: UDOT)

In certain cases, when a new bridge has a longer span, the foundation for the new abutment can be behind the existing abutment (i.e., in between the existing abutment and the pavement). Oregon DOT devised a methodology for this case. The methodology was implemented in the Cascade Highway South (OR213) Bridge over Washington Street project. Construction activities were carried out at night with temporary lane closures. Details and the construction sequence are shown in Figure 4-7. However, the Oregon DOT used this methodology to construct the sleeper slab foundation, which is also applicable to new abutment foundation construction.



(a) Plan



(b) Elevation

Note: Construction stages are denoted with the numerical labels shown in the above figures.

Foundation Construction Sequence under Nightly Lane Closures:

1. Install shoring. Remove existing paving slab as needed. Repair pavement as required prior to reopening a lane to traffic.
2. Install temporary slab support beams. Repair pavement as required prior to reopening a lane to traffic.
3. Excavate for pile cap and install temporary slabs. These slabs can be removed and reinstalled as needed for construction activities.
4. Remove the temporary slabs, drive piles, and reinstall the slabs.
5. Remove the slabs, construct pile cap, and reinstall the slabs.
6. Remove the slabs, install the roller system for bridge slide, and reinstall the slabs.

Figure 4-7. Foundation construction behind the abutment: details and construction sequence

4.3.2.2 Pier Foundation

Bridge pier foundation construction methodologies are summarized in Appendix A. For the case when a replacement bridge is on a new footprint, a majority of the foundation types listed in Figure 4-1 can be considered. The foundation type and the construction method need to be selected after evaluating the impact on the existing bridge stability, headroom, site accessibility, and the cost. In the majority of the cases documented in Appendix A, stability considerations and headroom limitations resulted in specifying shallow foundations, micropiles, and drilled shafts. The use of a shallow foundation is limited to the presence of competent material strata near the ground surface. For installation of all the deep foundations, headroom is a constraint. Micropiles and drilled shafts are exceptions, and have been constructed with 5 to 6 ft headroom. When the head room is limited, installation between the girders will increase the headroom by another few feet. If other constraints, such as the presence of utilities, do not interfere, foundations can be installed outside the bridge footprint. The next section discusses the substructure options when the new foundation is installed outside the footprint.

4.4 SUBSTRUCTURE ALTERNATIVES

As documented in Appendix A, space constraints for substructure construction while the existing bridge is in service allowed cast-in-place construction for abutments and piers. Cast-in-place construction is an option when substructure construction does not impact mobility.

In addition to using typical columns and bent caps, hammerhead piers and piers with two out triggers were used. Straddle bents are an option when the foundations are constructed outside the bridge footprint. Even though not explicitly used for ABC construction, Figure 4-8 shows two examples of using straddle bents. Precast posttensioned segmental piers and prestressed or posttensioned bent caps are also options for ABC (Figure 4-9 and Figure 4-10). Designs of these substructures require careful consideration for construction loads, especially the horizontal forces generated during bridge slide operation. Temporary bracings can be provided to resist the horizontal forces during the slide.

Figure 4-8. Drilled shaft construction outside the bridge footprint (Brown et al. 2010)

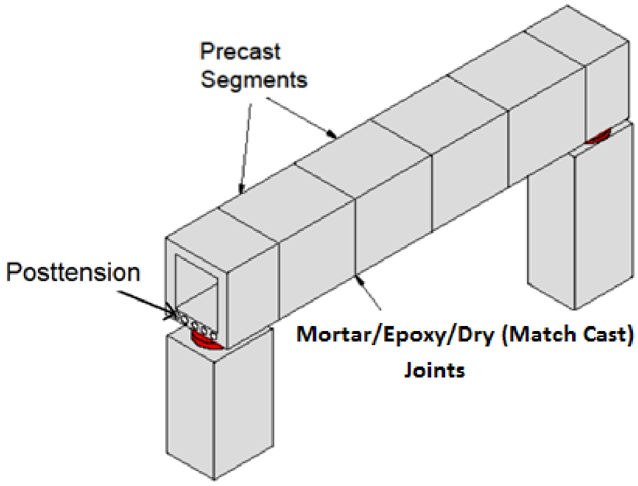


Figure 4-9. Precast segmental bent cap (Source: CSU 2015)

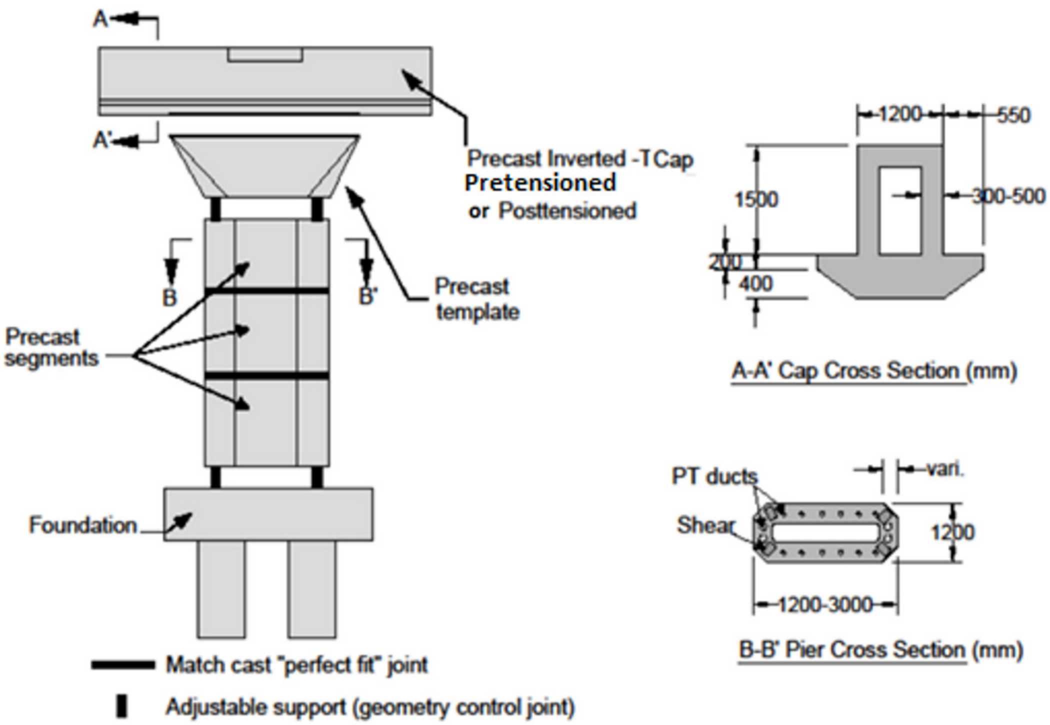


Figure 4-10. Precast segmental columns and precast prestressed/posttensioned bent cap (Source: Shahawy 2003)

4.5 SUMMARY

This chapter presents a foundation type classification based on the degree of disturbance to the surrounding soil during foundation installation. Also, a scoping methodology is presented to help with foundation reuse, retrofit, or replacement decisions. Lastly, methodologies for foundation reuse, retrofit, and replacement are presented. Appropriate methodologies are extracted from large number of case studies. As a result, the following conclusions are developed:

- Shallow foundations, micropiles, and drilled shafts with supported excavations are recommended within the vicinity of existing foundations.
- Drilled shafts and micropiles can be installed with limited headroom. Headroom of 5 to 6 ft is often adequate.
- Reuse of foundations is recommended when possible. Only Illinois DOT developed guidelines and an analysis procedure for foundation reuse. The use of Illinois DOT guidelines and procedures is recommended until additional research is conducted to develop guidelines and procedures for reusing foundations specific to Michigan bridges.
- When foundation reuse is considered, the existing foundation lateral load capacity needs to be evaluated since foundations were not designed for construction loads from construction methods such as bridge slides.
- Development of a program to document unknown foundations is recommended. Documenting the foundation will increase the reuse potential.
- Typically, cast-in-place construction is used for substructure construction while the existing bridge is in-service. Precast segmental columns and bent caps can be specified to minimize the onsite construction duration and enhance construction quality.

5 COST AND BENEFIT ANALYSIS OF ABC

5.1 OVERVIEW OF COST AND BENEFIT PARAMETERS

The construction cost of an ABC project is usually higher and ranges between 6% and 21% over the cost estimate of traditional construction (FHWA 2011). Complexity, risk, and time constraints are the three main factors that contribute to the additional construction cost. ABC is new and the bridge community is gaining experience through limited implementations as demonstration projects. The strict time constraints always need to be a part of ABC projects in order to reduce the mobility impact time. These time constraints require innovative methodologies, such as SPMT move and SIBC, to be deployed and additional work before on-site construction; thus, lead to additional costs. ABC includes several benefits to the agency and users (FHWA 2013b). At present, during the maturing process of ABC, the emphasis is to standardize design, detailing, equipment, and construction process as well as to educate and allow local contractors build experience. As the ABC project delivery methods transition to common practice, costs are expected to be comparable or lower than the conventional construction cost (UDOT 2008).

The framework for project scoping presented in Chapter 3 can be used to evaluate CC, PBES, SPMT move, and SIBC delivery alternatives for a specific site. During that process, apart from the cost of material and labor for constructing the bridge, additional costs need to be considered for ABC specific activities in contrast to CC. These additional costs are described below:

- Prefabrication, shipping and handling, equipment, and use of specialized materials
- Right-of-way (ROW) acquisition for PBES equipment staging, if limited ROW available on FI
- Utility relocation (for deploying specialized equipment or procedures)
- Specialty equipment/contractor for SPMT move
- Mobilization for SPMT move
- Travel path preparation for SPMT move
- Staging area preparation for SPMT move
- Temporary structures for SPMT move
- Specialty contractor for SIBC

- Equipment and accessories for SIBC
- Preparing and operating for SIBC
- Temporary structures for SIBC
- ROW acquisition for SIBC, if limited.

These additional costs are parameters analyzed and quantified for the cost-benefit analysis. This chapter describes the methodology of cost calculations and estimates for SPMT move and SIBC specific costs. The cost estimates developed in this chapter are based on the data analyses from completed ABC projects, traffic data, and site-specific data.

Traditionally, for cost-benefit analysis of ABC, the benefit parameters are limited to detour length and duration of travel on the detour. From these, the savings in user cost are calculated and compared to the cost specific to the ABC alternative. The savings in user cost due to mobility impact time reduction is considered as a benefit for justifying the ABC (FDOT 2005; FHWA 2011). In this research, apart from the savings in the user cost, several other benefit parameters are considered for the cost-benefit analysis. The benefit parameters are listed in Table 5-1.

Table 5-1. Benefit Parameters

	Benefit Parameter
Quantitative Parameters	1. Level of service (LOS) on facility carried (FC) 2. Impact on nearby major intersection/highway-rail grade crossing with full closure 3. LOS on feature intersect (FI) 4. Impact on nearby major intersection/highway-rail grade crossing due to FI traffic 5. LOS on detour 6. Maintenance of traffic (MOT) cost 7. Life-cycle cost 8. User cost 9. Economic impact on surrounding communities 10. Construction duration.
Qualitative Parameters	1. Economic impact on surrounding businesses 2. Stakeholders' limitations 3. Seasonal limitations 4. Risk for traffic within work zone 5. Site condition complexities 6. Environmental protection near and within the site.

The respective benefits achieved from the above listed parameters are described below:

- The quantitative parameters 1-5 represent the impact of the traffic on respective roadway; their significance was discussed in Chapter 3. These parameters contribute to the benefit column based on the preference ratings calculated using the Mi-ABCD analysis. For example, concerning the impact on traffic parameters, a high preference rating indicates that there is a need to reduce the impact.
- The *MOT, life-cycle*, and *user cost* parameters are calculated based on the cost data presented in Chapter 3. These parameters contribute to the benefit column as these costs are reduced by implementing ABC. The benefits are observed by the reduced on-site construction duration and the improved long-term durability performance of bridges constructed using ABC. The *MOT cost* is defined as the unit cost per day for the MOT operations. The *life-cycle cost* includes initial construction cost, cost of maintenance and repairs throughout the bridge service life, and disposal cost or salvage value at the end of service life. The *user cost* includes driver delay costs due to work-zone, vehicle operating cost for all vehicles types, and the cost of accidents within the work-zone.
- The parameters, *economic impact on surrounding communities* and *economic impact on surrounding businesses*, contribute to the benefit column because ABC reduces the duration of traffic disruption on FC and FI.
- The parameters, *stakeholders' limitations*, *seasonal limitations*, and *construction duration* (i.e., FC closure duration), contribute to the benefit column because those limitations are satisfied if ABC is implemented.
- The *risk for the traffic within work zone* increases the liability to the contractor with the increased duration of construction activities. With ABC, the duration of construction activities interfering with traffic are decreased. In this case, ABC also reduces the contractor lump sum costs.
- The parameters, *site condition complexities* (e.g., viaduct over rapids, deep valley, or restricted site access) and *environmental protection near and within the site*, necessitate special considerations to fulfill respective requirements. These parameters contribute to the benefit column in the case of PBES implementation as described in

Chapter 3. For example, when these parameters are of high significance, implementing ABC will overcome complexity and help protection.

The significance of the initial cost of ABC that is determined only based on the direct cost is diminished when all the benefits are considered over the life span of the bridge.

5.2 COSTS SPECIFIC TO SPMT MOVES

5.2.1 Mobilization Cost

The SPMT move mobilization cost is calculated based on the number of required SPMT axle lines, transportation distance of the SPMT axles (distance to project site) and unit transportation cost of an axle line. The data required for estimating the mobilization cost was acquired from a pool of completed ABC projects. Appendix C includes the data extracted from the projects. Following the analysis of data, a set of equations is derived for the mobilization cost.

The number of SPMT axle lines needed to move a bridge span is a function of the superstructure weight. To estimate the superstructure weight, representative values of concrete and steel girder bridge superstructure weights, in kip/ft^2, were calculated. The unit values of the superstructure weight are shown in Table 5-2. These values are calculated from statistical analyses of completed ABC projects and normalized with the deck area of the superstructure. A cluster analysis was performed by assembling two sets of data: the weight of superstructures with steel girders and with prestressed concrete girders. The deck thicknesses of the completed ABC projects were different, and unit weight of concrete was also changing. The representative unit values for the superstructure weight shown in Table 5-2 are for a deck thickness of 9 in. and normal weight concrete (150 lb/ft^3 unit weight). The number of axle lines required to move a bridge superstructure is estimated from the statistical relationship given in Eq. 5-1.

Table 5-2. Representative Unit Values for Superstructure Weight

Superstructure Type	Representative Unit Value (kip/ft^2)
Steel girders with a 9 in. normal weight concrete deck	0.195
Prestressed concrete girders with a 9 in. normal weight concrete deck	0.279

$$n = 5E^{-10}(W^3) - 6E^{-06}(W^2) + 0.0337(W); \qquad n \in \{k \mid \exists i \in \mathbf{N}, k = 2i\} \qquad (5\text{-}1)$$

where: *"n"* is the number of required SPMT axle lines (belongs to the set of even natural numbers), and *"W"* is the superstructure weight per span (kips).

Eq. 5-1 was derived from regression analysis (Figure 5–1). For this purpose, superstructure weights and the number of axle lines used during each project were tabulated from the completed SPMT move projects. The comprehensive list of completed ABC projects was presented in Chapter 2. Eq. 5-1 is a very good fit to the data with a coefficient of determination, R^2, of 0.9478 (where $R^2 = 1.0$ represents exact fit).

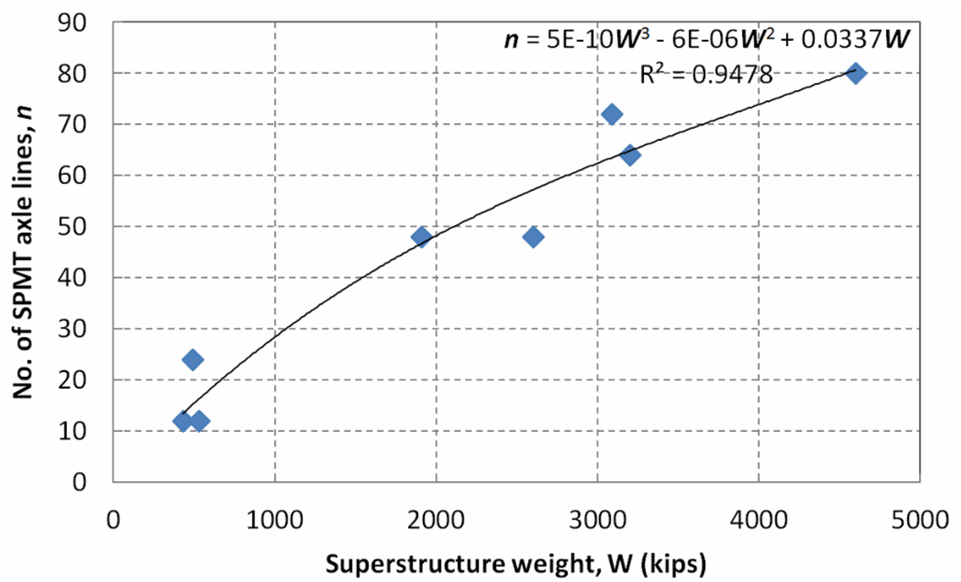


Figure 5–1. Relationship between number of axle lines and the superstructure weight

Eq. 5-1 (established for estimating the number of SPMT axle lines, based on the superstructure weight obtained from completed ABC projects) can be fine-tuned as more data becomes available from future implementations. The data used for the regression analysis is from ABC projects where SPMTs with 25T (55.12 kips) axle line capacities were used.

The data used for *the regression analysis* includes the Utah Pioneer crossing (single span) over I-15 moved from two lift points. Being one of the first SPMT move implementations in the U.S., 80 axle lines were used for a 4600 kip superstructure. Four SPMT modules, each with 10 axle lines, were combined providing a total of 40 axle lines at each lift point.

As part of the regression analysis, linear, 2nd degree polynomial, 3rd degree polynomial, 4th degree polynomial, and power curves were test-fit to the data. The statistical tests (paired two sample t-Test and single factor ANOVA) were also performed. Among the polynomials, the 3rd degree given in Eq. 5-1 yielded the highest P-values for both of the statistical tests (Table 5-3). P-value represents the level of acceptance of the null hypothesis (i.e., the corresponding curve is a best-fit). Thus, the statistical tests indicated that Eq. 5-1 is the best fit for the data. The regression and statistical analyses data are presented in Appendix C.

Table 5-3. P-values for the 3rd Degree Polynomial

Statistical test	P-value
Paired two sample t-test	0.743
Single factor ANOVA test	0.954

Ultimately, the mobilization cost for a project is calculated using Eq. 5-2 that includes the number of required SPMT axle lines (*n*) calculated from Eq. 5-1, the estimated distance (*d*) from a SPMT equipment hub, and the unit cost for transportation (*uct*).

$$\text{Mobilization Cost (\$)} = k \times d \times uct; \quad k = \left\lceil \frac{n}{6} \right\rceil \equiv Roundup\left(\frac{n}{6}\right) \qquad (5\text{-}2)$$

5.2.2 Travel Path Preparation Cost

Travel path preparation cost is also proportional to superstructure weight, SPMT axle loads, allowable soil bearing capacity at the site, and distance from the staging area to the new bridge. Appendix C includes the data collected from completed SPMT move projects for this purpose. An equation is derived to represent the travel path preparation cost. The derivation process is presented in this section.

The length of the travel path and allowable ground bearing pressure ranges given in Chapter 3, under the *site-specific data,* were used for calculating travel path preparation cost. Factored bearing pressure is calculated from superstructure weight and SPMT type. Allowable bearing pressure is estimated based on the soil type at the site. The factored and allowable bearing pressure ranges are correlated to an *ordinal capacity*, as shown in Table 5-4. The *ordinal capacity* simplifies the calculation process by comparing the factored bearing pressure and allowable bearing pressure. As an example, if the factored bearing pressure is 9 k/ft^2, row 1 of Table 5-4 is referred, and an *ordinal capacity* of 1 is used for further calculations. If the allowable bearing pressure is 2 k/ft^2, row 5 of Table 5-4 is referred, and an *ordinal capacity* of 5 is selected.

SPMT technical specifications from Mammoet Scheuerle 2nd Gen, 3rd Gen, 4th Gen, Mammoet Kmag 2nd Gen, Sarens, and Sterling were reviewed. The ground bearing pressure and the data from the technical specifications were used to calculate the required minimum base thickness as part of the travel path preparation. Also, based on the thickness requirements, a rating was assigned and defined as *significance category* (Table 5-5). Further, the differential between the factored bearing pressure and allowable bearing pressure is defined by an ordinal rating value (Table 5-6).

The following example shows the process to calculate the required base thickness for the travel path:

The factored bearing pressure = 9 k/ft^2
Ordinal capacity from Table 5-4 = 1 *(row 1 of the table)*
The allowable bearing pressure = 2 k/ft^2
Ordinal capacity from Table 5-4 = 5 *(row 5 of the table)*
Difference between ordinal capacities of allowable and factored bearing pressures
= 5 – 1 = 4
Significance category from Table 5-6 = V *(row 6 of the table)*
Min. base thickness required from Table 5-5 = 17.50 in. *(row 5 of the table)*

Table 5-4. Correlation of Factored Bearing Pressure and Allowable Bearing Pressure

Factored bearing pressure (k/ft^2)	Ordinal capacity	Allowable bearing pressure (k/ft^2)
>8	1	>8
>6 to ≤ 8	2	>6 to ≤ 8
>4 to ≤ 6	3	>4 to ≤ 6
>2 to ≤ 4	4	>2 to ≤ 4
≤ 2	5	≤ 2

Table 5-5. Minimum Base Thickness Required for Travel Path Preparation

Minimum base thickness (in.)	Significance category
1.25	I
3.00	II
4.50	III
9.50	IV
17.50	V

Table 5-6. Significance of the Difference between Factored and Allowable Bearing Pressure Ordinal Capacities

Difference in ordinal capacities from Table 5-4 ***[Ordinal capacity of allowable bearing pressure – Ordinal capacity of factored bearing pressure]***	**Significance category**
Allowable bearing pressure > Factored bearing pressure	I
0	I
1	III
2	V
3	V
4	V

Finally, the cost for preparing the travel path is calculated from Eq. 5-3. Eq. 5-3 includes length of travel path (*L*), width of travel path (*b*), minimum required base thickness (*t*), and unit cost of base preparation (*ucbp*). The *L* is obtained from the site-specific data, the *b* is taken equal to the new bridge length, and the *t* is calculated using the procedure presented above. The unit cost is obtained from market rates. A sample breakdown of the unit cost from a Tier 2 SPMT move project is shown in Table 5-7.

$$\text{Preparing Travel Path Cost (\$)} = L \times b \times t \times ucbp \tag{5-3}$$

Table 5-7. Sample Unit Cost for Base Preparation

	Unit cost for base preparation ($ per CY) [2014 dollar]	**Unit cost for base preparation ($ per in. depth of sq. ft)**
Subbase grading B *	15.05	0.0465
Common fill	11.25	0.0347
Structural fill	11.35	0.0350
	Total:	**0.1162**

* *"Grading B" for a "subbase" complies with ASTM D2940 (standard specification for graded aggregate material for bases or subbases for highways or airports)*

5.2.3 Staging Area Preparation Cost

Staging area preparation cost is proportional to the superstructure weight, factored bearing pressure, allowable bearing pressure, required base thickness, and the size of the staging area. From the analysis of SPMT move projects listed under the literature review, the staging area, in terms of square feet, is determined to be proportional to the new superstructure deck area multiplied by a constant factor (F). The data obtained from completed SPMT move projects gave the constant factor, F, as 1.8. The staging area preparation cost is calculated using Eq. 5-4.

$$\text{Staging Area Preparation Cost (\$)} = F \times A \times ucsap \tag{5-4}$$

The factor, *F*, is used to calculate the square footage of a staging area by prorating the new bridge superstructure area, *A*. The *ucsap* is the unit cost for staging area preparation in $/sq. ft. The *ucsap* is calculated by obtaining the staging area preparation cost, a lump sum cost from the completed SPMT move projects, and normalizing to the unit area and one span cost for each project. The *ucsap* is calculated as $2.24 in terms of 2014 dollar value using the consumer price index (CPI) converter (Williamson 2014). A typical structural fill is assumed to be used for the staging area preparation. The factor *F* and *ucsap* can be updated when data is available from future implementations and converting *ucsap* to the present value using the available CPI converter.

5.2.4 Temporary Structures

The temporary structure cost for an SPMT move project depends on the type of temporary supports. From the review of completed SPMT move projects, the superstructure is typically supported at the staging area using the following types of temporary supports:

1. Temporary shoring
2. Temporary steel beams on ground
3. Shipping containers.

The temporary shorings are designed for the superstructure weight and construction loads using the AASHTO temporary structures guide specifications. The temporary steel beams on ground require special jacks, such as climbing jacks, along with SPMT move for lifting the superstructure to its final elevation before the move. The shipping containers are the cheapest option; however, they are not highly reliable engineered products and should not be approved.

The temporary structure cost for SPMT move is calculated using Eq. 5-5 that includes *the superstructure weight (*W*) per span* and unit cost for the temporary structure (*ucts*).

$$\text{SPMT Temporary Structures Cost (\$)} = W \times ucts \qquad (5\text{-}5)$$

The *ucts*is calculated by obtaining the temporary structure's cost, a lump sum cost (from completed SPMT move projects and normalizing to superstructure weight), one span, and type of temporary support structure as shown in Table 5-8. The *ucts* is calculated for 1 kip weight of superstructure per span in terms of *2014 dollar value*. The *ucts* can be updated when data is available from future implementations and converting to the present value using the available CPI converter.

Table 5-8. Representative Temporary Structure Cost

Temporary structure type	Representative unit cost for temporary structure per 1 kip span weight (2014 dollar)
Temporary shoring	59
Temporary steel beams on ground	10
Shipping containers	5

5.2.5 Specialty Equipment/Contractor Cost

SPMT move is subcontracted, as are other accessory equipment, manpower, and logistics related to a bridge move. The cost is included in the bid as a lump sum. The cost that is not included in this category is considered as the specialty equipment/contractor cost. The unit cost for the specialty equipment/contractor (*ucsec*) is calculated from the analysis of data obtained from completed ABC projects. The analysis showed that this cost is proportional to the superstructure area (A) and calculated using Eq. 5-6. The *ucsec* is calculated by obtaining the lump sum cost of the specialty SPMT move contractor from completed SPMT move projects and normalizing to unit superstructure area. The *ucsec* is calculated as \$67 in terms of a *2014-dollar value.* The *ucsec* represents the complete cost of the specialty SPMT move contractor inclusive of the bridge move logistics. The *ucsec* can be updated as new data is available from future implementations and converting to the present value using the available CPI converter.

$$\text{Specialty Equipment/Contractor Cost (\$)} = ucsec \times A \qquad (5\text{-}6)$$

5.3 COSTS SPECIFIC TO SIBC

5.3.1 Specialty Contractor Cost

The specialty contractor cost is an additional cost for an SIBC project when the slide operation is subcontracted. This cost is specific to the general contractor and depends on the contracting type. If the general contractor performs the slide-in operation, this cost is included under “equipment and accessories, and preparing and operating” which is discussed below.

5.3.2 Equipment and Accessories, Preparing and Operating Cost

Data from the completed ABC projects often reported the cost for equipment and accessories, along with preparing and operating the SIBC collectively as slide operation cost. A cost equation is developed from the data for calculating the collective slide operations cost for new projects. The cost is data correlated to the superstructure weight per span (W) and unit slide cost per span (*uscps*), as shown in Eq. 5-7. The *uscps* is the combined equipment and accessories, along with preparing and operating cost.

$$\text{Equipment \& Accessories+Preparing \& Operating Cost (\$)} = W \times uscps \qquad (5\text{-}7)$$

To estimate the superstructure weight per span, representative unit weight values in kip/ft^2 for steel girder and prestressed concrete (PC) girder bridges are shown in Table 5-2. Representative *uscps* is calculated by obtaining the slide operation cost, a lump sum cost, from completed SIBC projects and normalizing to superstructure weight, one span, and the respective category shown in Table 5-9. The *uscps* is calculated for 1 kip weight of superstructure per span in terms of 2014-dollar value. Appendix D presents the analysis data. The *uscps* can be updated when data is available from future implementations and converting to the present value using the available CPI converter.

Table 5-9. Representative Equipment and Accessories, and Preparing and Operating Cost

Category	Representative equipment and accessories and preparing and operating cost per 1 kip per span (2014 dollar)
Bridge slide with sliding of both old and new structures	80
Bridge slide with diverting traffic on new structure while old bridge is demolished	70
Bridge slide with complete closure of roadway, i.e., without traffic diversion	64

5.3.3 Temporary Structures for SIBC

The temporary structures cost data for SIBC projects are compiled from completed SIBC projects. Statistical analysis of this data showed that the cost is also directly proportional to the superstructure weight. The temporary structures cost for SIBC projects is proportional to the superstructure weight per span (W) and unit temporary structure cost per span (*utscps*). Eq. 5-8 is defined to calculate SIBC temporary structure cost.

$$\text{SIBC Temporary Structure Cost (\$)} = W \times utscps \tag{5-8}$$

The representative unit values in kip/ft^2, for the superstructure weight of steel girder and PC girder bridges, presented in Table 5-2, are also valid here. Hence, the superstructure weight (W) can be calculated using Table 5-2 with the deck area of the new structure. The data analysis indicated three cost categories, which are the following:

A. The new superstructure on temporary supports is used as the detour. Temporary substructure welding is performed as per AWS D1.5.
B. No traffic is allowed on the new superstructure while on the temporary substructure. Temporary structure welding is performed as per AWS D1.1.
C. As the new superstructure is slid from the temporary substructure onto the permanent substructure, the old superstructure is slid out onto an adjacent temporary substructure. In this case, it is assumed that the new bridge was not used as a detour while on the temporary substructures. Hence, the substructure welding is performed as per the AWS D1.1

The representative *utscps* is calculated by obtaining the temporary structure cost (a lump sum cost) from completed SIBC projects and normalizing to superstructure weight, one span, and the respective category shown in Table 5-10. The *utscps* is calculated for 1 kip weight of superstructure per span in terms of 2014-dollar value. For multiple spans, the SIBC temporary structure cost per span is multiplied by the number of spans. Appendix D presents the statistical cluster analysis data used for temporary structure cost calculation. The *utscps* can be updated when data is available from future implementations and converting to the present value using the available CPI converter.

Table 5-10. Representative Temporary Structure Cost w.r.t to Project Category

Category	**Representative temporary structure cost per 1 kip per span (2014 $)**
Bridge slide with sliding of both old and new structures	66
Bridge slide with diverting traffic on new structure while old bridge is demolished	52
Bridge slide with complete closure of roadway, i.e., without traffic diversion	50

5.4 UTILITY RELOCATION COSTS

The utility relocation costs related to ABC can be due to PBES equipment staging, deploying SPMT equipment, or for constructing SIBC temporary structures. This cost varies based on the risks associated with relocating the utilities. The risk level, in turn, depends on the number of affected utilities and the estimated duration for utility relocation (Sturgill et al. 2015). The research by Sturgill et al. (2015) to expedite and streamline utility relocations for road projects provides correlations for the risk level to the utility phase authorization amount. The research provides the correlations as presented in the Table 5-11 and Table 5-12. The costs are given for the year 2014 and can be updated using the CPI convertor (Williamson 2014).

Table 5-11. Risk Level Correlated to Utility Relocation Duration and Number of Utility Relocations

Risk Level	Number of Utility Relocations	Utility Relocation Duration
Low	Less than 3	Less than 365 days (1 year)
Medium	Between 3 and 6	Between 365 and 1095 days (3 years)
High	Greater than 6	Greater than 1095 days

Table 5-12. Risk Level Correlated to Utility Phase Authorized Amount

Risk Level	Utility Phase Authorized Amount	Representative Utility Relocation Cost (2014 dollar)
Low	Less than $300,000	$300,000
Medium	Between $300,000 and $600,000	$450,000
High	Greater than $600,000	$600,000

The correlations in Table 5-11 and Table 5-12 are based on the data from 1,966 roadway projects that required utility relocations. The correlations can be used to estimate the range of cost or a representative cost for utility relocation. A project requiring relocation of one or more main gas, oil or water lines will incur significant cost. In calculating the relocation cost of complex utilities, the risk level can be specified as high, and the maximum representative utility relocation cost can be assigned.

5.5 FOUNDATION COST ESTIMATES

The type of foundation specified for the project determines the cost. The foundation cost data was gathered from project bid tabs of ABC projects (FHWA 2015). The estimates for foundation cost for each foundation type are calculated from the analysis of data from the completed ABC projects. The cost data is calculated per linear foot of foundation with respect to foundation type.

Analysis of the literature showed that the cost estimating methodology is highly dependent on the contracting method and contract type of the project. The common types of contracting methods are described in Table 5-13, and common contract types are defined in Table 5-14.

Table 5-13. Contracting Methods (Kenig 2011)

Contracting Method	Description
Design-Bid-Build	Traditional contracting method. The owner procures a design and bid package from an independent designer, uses a competitive procurement process to get bid prices for all work required to build the project as specified, and then selects a constructor to build the project, usually on the basis of Low Bid procurement.
Design-Build	One firm assumes responsibility for both the design and construction of the project.
Construction Management (CM) at-Risk	The owner has separate contracts with the CM at-Risk and the designer. The CM at-Risk holds the trade contracts and takes responsibility for the performance of the work.
Integrated Project Delivery (IPD)	The owner, the designer, the contractor, and other primary parties sign one multi-party agreement.

Table 5-14. Contract Types (Kenig 2011)

Contract Type	Description
Lump Sum	The contract has a set price in exchange for providing a prescribed scope.
Guarantee Maximum Price	The owner agrees to reimburse the cost of the work up to a prescribed ceiling amount.
Cost Plus a Fee	The owner agrees to cover the construction cost and reimburse the contractor a percentage (fee) of the total construction cost.
Target Price	The project participants establish a target price for the project and then work together to maximize the value that the owner receives for that amount.

ABC projects can be constructed under any contracting method and contract type; therefore, many cost estimating methodologies might apply according to level of detail required for the foundation cost estimates. The cost estimating methodologies can be classified into the following four categories:

1) Parametric method: This is applied to projects in the planning, scoping, or early design stages. It involves techniques that use historical data to define the cost of typical transportation facility segments, such as cost per lane mile, cost per interchange, cost per square foot, and cost per intersection.
2) Historical bid-based method: This is appropriate when design definition has advanced to the point that quantification of units of work is possible. These methods apply historical unit costs to the measures of work items/activities to determine the total cost for an item.

3) Cost-based method: This includes determining the contractor's cost for labor, equipment, materials and a specialty subcontractor's effort to complete the work for an item or a group of items. A reasonable amount for contractor overhead and profit is also added. This method is preferable on unique projects or where geographical influences, market factors, and volatility of material prices is assumed to cause the historical bid-based method unreliable.
4) Risk-based method: This involves simple or complex analysis based on inferred relationships between cost, schedule, and events in a project. This method uses a variety of techniques to develop the preliminary cost estimate for a given type of work, such as historical data, cost based estimating, and judgment from experts. Risk elements are applied to the preliminary cost estimate using Monte Carlo Simulations to obtain a probable range for project cost and schedule.

In this project, the historical bid-based method was used to develop foundation cost estimates from the data gathered from completed ABC projects. The historical bid-based method was considered appropriate because quantifying units of work items/activities and assigning representative unit costs for such work items/activities was possible. Cost analysis was performed to obtain the cost estimates per linear foot of foundation from the completed ABC projects' bid tabs. The cost analysis was essential because several foundation work items/activities were measured in different units rather than linear foot of foundation. The cost estimates obtained for shallow and deep foundation types are presented in Table 5-15. The cost estimates are presented as low cost, high cost and representative cost for each foundation type. The representative costs are obtained using typical factors from historical cost databases and knowledge of market conditions (WSDOT 2008). The cost estimates are converted to the present value using the CPI converter (Williamson 2014). Table 5-15 also shows the work items/activities associated with each foundation type.

Table 5-15. Cost Estimates for Foundation Types

Foundation Type	Displacement Type	Unit	Low Cost ($) (2014 dollar)	High Cost ($) (2014 dollar)	Representative Cost ($) (2014 dollar)	Work Item/Activity
Shallow Foundation						
Spread Footing	N/A	CUFT	57.23	114.32	67.65	Excavation Concrete Reinforcing steel
Deep Foundation						
H-Pile	Low	LF	84.38	199.22	101.00	H-pile (furnish and drive) Test pile Pile point
Open-Ended Pipe Pile	Low	LF	90.43	151.36	101.30	Steel pipe pile Steel pipe pile test
Closed-Ended Pipe Pile	High	LF	178.58	178.58	178.58	Concrete filled steel pipe pile (furnish and drive) Test pile (furnish and drive) Dynamic pile load test Splices
Precast Concrete Pile	High	LF	125.14	347.73	216.91	Precast prestressed concrete pile Test pile
Drilled Shaft*	None	LF	1,071.00	2,055.52	1,230.92	Drilled shaft Shaft excavation Permanent casing Load test Integrity testing
Micropile	None	LF	292.77	523.36	382.58	Micropile Micropile demonstration

* 60 in. diameter

Inputs required for the preliminary estimate of foundation cost include the foundation type and associated construction activities based on site-specific conditions. For an ABC project, a preliminary estimate during the project scoping process can be used as the representative cost presented in Table 5-15. The representative cost data can be updated by incorporating the data from future implementations based on the work items/activities, and converting to present value using any available CPI converter.

5.6 USER AND LIFE-CYCLE COST MODELS

5.6.1 User Cost

The user cost analysis considers the cost incurred by the facility carried (FC) traffic as well as the feature intersected (FI) traffic affected by the bridge construction. The components of user cost are driver delay costs (DD), vehicle operating cost (VOC), and accident costs (AC).

These costs are calculated from Eqs. 5-9, 5-10, and 5-11 (Ehlenand Marshall 1996; Walls and Smith 1998).

$$DD = \left[\frac{L}{S_a} - \frac{L}{S_n} \right] \times ADT \times N \times w \qquad (5\text{-}9)$$

$$VOC = \left[\frac{L}{S_a} - \frac{L}{S_n} \right] \times ADT \times N \times r \qquad (5\text{-}10)$$

$$AC = L \times ADT \times N \times (A_a - A_n) \times C_a \qquad (5\text{-}11)$$

where, L is length of the affected roadway due to bridge construction (i.e., work zone length); S_a is speed limit within the work-zone; S_n is normal speed limit of the roadway; ADT is average daily traffic of the roadway; N is construction days affecting the work zone; w is weighted-average cost per hour for the personal and commercial drivers based on truck traffic; r is weighted-average vehicle cost per hour for the personal and commercial vehicles based on truck traffic; A_a is accident rate per vehicle-mile due to work zone; A_n is normal accident rate; and C_a is cost per accident.

Eqs. 5-9 and 5-10 are based on the extra time to travel arising from the reduced speed limit at the work zone. For SPMT move and SIBC, typically, both of the FC and the FI are closed during the ABC window (i.e., move or slide weekend). The components of user cost in this case are DD and VOC costs incurred by the FC and FI users. These costs can be calculated from Eqs. 5-12 and 5-13.

$$DD = \left[T_D - T_{Br} \right] \times V_T \times T_M \times w \qquad (5\text{-}12)$$

$$VOC = \left[T_D - T_{Br} \right] \times V_T \times T_M \times r \qquad (5\text{-}13)$$

where: T_D is time to travel via detour; T_{Br} is time to travel on the bridge for FC user cost or under the bridge for FI user cost; V_T is volume of traffic on the roadway to be impacted during the ABC window; T_M is mobility impact time for the roadway in days; and w and r are the same as defined in Eqs. 5-9 and 5-10.

Note that the method for calculating the user cost from these equations and parameter values may need to be modified based on the project delivery alternative. For example, with the public outreach efforts associated with SPMT move and SIBC, reduced traffic will be expected on FC and FI that require detour during the ABC window. In this case, a lesser percentage of ADT needs to be considered as V_T in Eqs. 5-12 and 5-13 for user cost of respective roadway. On the other hand, when implementing the SIBC method with full-closure of FI for the entire project duration, the user cost for FI traffic is calculated using the entire ADT as V_T and entire project duration as T_M in Eqs. 5-12 and 5-13.

When implementing the CC method, typically, the FC traffic and FI traffic will experience work zone delays. Thus, the user costs for both FC and FI traffic are calculated using Eqs. 5-9, 5-10, and 5-11. Similarly, when implementing the PBES, the FI traffic will face work zone delays. Thus, the user cost for FI traffic is also calculated using Eqs. 5-9, 5-10, and 5-11. The FC traffic, with PBES, can either be closed for the entire project duration or remain open with staged construction. For the full closure case, the user cost for FC traffic is calculated using Eqs. 5-12 and 5-13; whereas, for staged construction, the user cost for FC traffic is calculated using Eqs. 5-9, 5-10, and 5-11.

5.6.2 Life-Cycle Cost

The life-cycle cost (LCC) represents the estimated cost over the life of the structure that is constructed with a particular project delivery alternative. The LCC analysis includes calculating and comparing the LCC associated with various project delivery alternatives. To document and leverage LCC analysis models, LCC analysis procedures used in the U.S. and abroad were reviewed (Rister and Graves 2002; Rangaraju et al.2008; Bonstedt 2010; Chan et al. 2008; Kendall et al. 2008; and Lee et al. 2011).

The Net Present Value (NPV) economic analysis methodology is adopted for the LCC calculations. This method is based on the terminology and procedure adopted from *BridgeLCC* (NIST 2003) and *RealCost LCCA* (FHWA 2004) tools that are widely utilized in the US. The NPV of LCC for various project delivery alternatives is calculated using Eq. 5-14.

$$NPV(LCC) = IC + \sum_k [RC]\left[\frac{1}{(1+i)^{n_k}}\right] + [(-S)\ or\ (+D)]\left[\frac{1}{(1+i)^n}\right] \qquad (5\text{-}14)$$

where: *IC* is initial cost; *RC* is rehabilitation or repair cost; *S* is salvage value; *D* is disposal cost; *n* is number of years of LCC analysis (LCC analysis period); and *i* is real discount rate.

The *RC* is expected *k* number of times for a particular project delivery alternative during the life-cycle analysis duration of *n* years. The real discount rate, *i*, converts the cost of n^{th} year to the present value. The salvage value, *S*, is estimated from the remaining service life of the structure at the end of the life-cycle cost analysis duration of *n* years. The disposal cost, *D*, is the cost to demolish and remove the structure.

The LCC analysis needs to be performed by considering all the project delivery alternatives at once. To calculate the LCC for SPMT move and SIBC project delivery alternatives, the *IC* needs to include all the respective specialty costs. However, the *IC* need not include the liability cost for work zone traffic for SPMT move projects as the superstructure is built at a staging area. Conversely, for the CC, PBES, and SIBC project delivery alternatives, the *IC* needs to include the liability cost to the contractor for the traffic within the work zone.

In the LCC analysis, an uncertainty is the repair/rehab cost incurred during the service life of the bridge based on the structural system performance. A significant portion of the LCC cost incurs from the superstructure rehabilitation or repair throughout the service life of the structure. Thus, for the LCC analysis, considering the life-cycle performance of the superstructure is important. The SPMT move and SIBC methods can implement either cast-in-place construction or prefabricated elements assembly at the staging area for the superstructure construction. ABC, at this time, is performed using the material and construction specification developed for CC. In this case, the SPMT move and SIBC will have the same life-cycle performance of the superstructure in the case of cast-in-place deck construction (UDOT 2008). On the other hand, PBES at a staging area may exhibit a better life-cycle performance than the conventional PBES. This is due to unconstrained access and adequate time for assuring quality and concrete or grout curing. As a simple solution, for SPMT move and SIBC, the inputs for Eq. 5-14 can be estimated similar to CC and PBES based on the respective scheme until an adequate amount of performance data is available from ABC implementations. In the future, it is expected that ABC will be performed using material and construction specifications that will yield a superior product to CC. This is because critical construction activities, such as concrete wet curing time and setting time of grout that influence the durability of the bridge, are performed when the structure is on temporary supports and no longer influences the user cost. At that time, the LCC of ABC will be significantly lower than CC.

The LCC can be calculated using typical values from literature until more accurate data becomes available from future ABC projects. One of the assumptions for LCC analysis is that the service life of a bridge built using PBES is longer than the service life of a conventionally constructed bridge (i.e., CC project delivery alternative). With this assumption, service life of a CC bridge can be used as the LCC analysis period. Hence, a bridge built using the PBES method will have a remaining service life; thus, a salvage value, i.e., a dollar amount gained because of increased service life.

5.7 ANALYSIS OF COSTS AND BENEFITS OF ABC

The analysis of costs and benefits of ABC can be performed by incorporating the cost and benefit parameters discussed in Section 5.1. The costs that need to be obtained for respective ABC alternative are shown below in Table 5-16:

Table 5-16. ABC Alternative Costs for Cost-Benefit Analysis

PBES costs	SPMT move costs	SIBC costs
Construction	Construction	Construction
Prefabrication	Utility relocation	Utility relocation
Shipping and handling	Specialty equipment/contractor	Specialty contractor
Equipment	Mobilization	Equipment and accessories
Specialized materials	Travel path preparation	Preparing and operating
ROW acquisition for equipment staging	Staging area preparation	Temporary structure
	Temporary structure	ROW acquisition

The costs shown in Table 5-16 can be obtained based on the project specific data (discussed in Chapter 3) and other cost calculation procedures presented earlier in this chapter in Sections 5.2, 5.3, and 5.4. A few of the costs shown in Table 5-16 are not typical, such as specialized materials, ROW acquisition, and utility relocation; therefore, these costs may not be applicable and need not be considered based on the specific project.

The benefits can be quantified from the benefit parameters for respective ABC alternative shown below in Table 5-17.

Table 5-17. ABC Alternative Benefits for Cost-Benefit Analysis

PBES benefit	SPMT move benefit	SIBC benefit
LOS on FC	LOS on FC	LOS on FC
Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	Impact on nearby major intersection/highway-rail grade crossing with full closure of FC	Impact on nearby major intersection/highway-rail grade crossing with full closure of FC
LOS on FI	LOS on FI	LOS on FI
Impact on nearby major intersection/highway-rail grade crossing due to FI traffic	Impact on nearby major intersection/highway-rail grade crossing due to FI traffic	Impact on nearby major intersection/highway-rail grade crossing due to FI traffic
LOS on detour	LOS on detour	LOS on detour
MOT cost	MOT cost	MOT cost
Life-cycle cost	Life-cycle cost	Life-cycle cost
User cost	User cost	User cost
Economic impact on surrounding communities	Economic impact on surrounding communities	Economic impact on surrounding communities
Economic impact on surrounding businesses	Economic impact on surrounding businesses	Economic impact on surrounding businesses
Stakeholders' limitations	Stakeholders' limitations	Stakeholders' limitations
Seasonal limitations	Seasonal limitations	Seasonal limitations
Construction duration	Construction duration	Construction duration
Site condition complexities	Risk for traffic within work zone	
Environmental protection near and within the site	Number of clustered bridge replacement projects	

The benefit parameters shown in Table 5-17 can be obtained from the project-specific data and corresponding ordinal scale ratings (OSRs). The OSRs assignments for the above parameters were discussed in Chapter 3. Most of the benefit parameters for the ABC alternatives are typical; thus, they will have similar OSRs. The benefit parameters that will be different for the ABC alternatives are: (i) MOT cost, (ii) LCC, (iii) User cost, (iv) Risk for traffic within work zone, (v) Site condition complexities, and (vi) Environmental protection near and within the site. Among these, the parameters' MOT, LCC, and User cost are assigned OSRs corresponding to each project delivery alternative. The OSRs are assigned from differential value, $V(\%)$, and $OSR_{(V\%)}$ calculated using Eqs. 5-15 and 5-16, respectively.

$$V(\%) = \frac{\left|V_i - Max(V_{PBES}, V_{SPMT}, V_{SIBC})\right|}{Max(V_{PBES}, V_{SPMT}, V_{SIBC})} \times 100 \qquad (5\text{-}15)$$

where: V_i is the cost of alternative i for which the $V\%$ is needed; and V_{PBES}, V_{SPMT}, V_{SIBC} are the cost of respective ABC alternatives.

$$OSR_{(V\%)} = \begin{cases} 1 & \text{for: } 0 \le V(\%) < 20; \\ v+1 & \text{for: } 20 \le V(\%) \le 100; \\ & v = TRUNC\left(\dfrac{V(\%)}{10} - 1\right); \quad v \to \text{integer}[1,8] \end{cases} \tag{5-16}$$

In the cost-benefit analysis, the costs and benefits need to be compared using a consistent measure. The preference ratings can be used as a measure for comparing costs and benefits, because both costs and benefits can be represented as normalized preference ratings. After calculating the OSRs of all the benefit parameters, normalized preference ratings specific to benefit parameters can be calculated for each ABC alternative.

Similarly, for the cost parameters (Table 5-16), the normalized preference ratings for each ABC alternative can be calculated using Eqs. 5-15 and 5-16. The normalized preference ratings specific to cost parameters can be compared with the normalized preference ratings specific to benefit parameters of respective ABC alternative.

The cost-benefit analysis can also incorporate the CC alternative. In such case, the cost and benefit parameters for CC are as shown in Table 5-18.

Table 5-18. Cost and Benefit Parameters for CC Alternative

Cost parameters	Benefit parameters
LOS on FC	Construction cost
LOS on FI	Financial and political risk
LOS on detour	Contractor qualifications (experience)
Impact on nearby major intersection/highway-rail grade crossing due to FI traffic	Procuring distance of specialty equipment
MOT cost	Site condition complexities
Life-cycle cost	Scour or hydraulic complexities
User cost	Impact on utilities on the structure
Economic impact on surrounding communities	Feasibility of staged construction
Economic impact on surrounding businesses	Limitations for PBES construction
Stakeholders' limitations	Geometric complexity for SPMT move
Seasonal limitations	
Construction duration	
Risk for traffic within work zone (i.e., liability cost to the contractor)	
Environmental protection near and within the site	

The benefit parameters shown in the above Table 5-18 contribute to CC based on their significance discussed in Chapter 3. The cost and benefit comparison for CC can also be incorporated in the cost-benefit analysis of ABC alternatives using the normalized preference ratings measure as discussed above.

5.8 SUMMARY

The mobility impact restrictions imposed on ABC result in several benefits to the agency and users. However, ABC implementations, especially SIBC and SPMT move, require project specific innovative methodologies and preparatory work prior to on-site construction that leads to additional costs. The scoping process that involves evaluating the project delivery alternatives for a specific site needs to consider the additional costs associated with ABC. Thus, a cost-benefit analysis is warranted.

In addition to user costs, several other benefit parameters are considered for the cost-benefit analysis. The benefit parameters consist of quantitative and qualitative parameters. The quantitative parameters include cost parameters such as maintenance of traffic (MOT), user cost, and life-cycle cost. These costs contribute to the benefit parameters because of short work-zone construction duration and anticipated long-term durability performance of ABC. The contribution of the other quantitative parameters to benefits is evaluated using the Mi-ABCD methodology where the quantitative values are converted to preference ratings. The qualitative parameters contribute to the benefit parameters by special considerations and limitations imposed on a bridge project can be fulfilled with ABC rather than CC.

Normalized preference ratings are described as a measure for comparing costs and benefits. This concept is similar to the normalized preference ratings calculation methodology presented in Chapter 3. The methodology is based on obtaining ordinal scale ratings (OSRs) of the quantitative and qualitative parameters. The OSRs are used for calculating the normalized preference ratings for each of the project delivery alternatives. The impact of increased initial cost of ABC is often balanced by the benefit parameters when considered over the life span of the bridge.

Formulations are developed for estimating SPMT move and SIBC specific costs, which are specialty equipment/ contractor cost for SPMT move, mobilization for SPMT move, preparing a travel path for SPMT move, preparing a staging area for SPMT move, temporary structures cost for SPMT move, specialty contractor cost for SIBC, SIBC equipment and accessories, SIBC preparing and operating, and temporary structures cost for SIBC. Additionally, utility relocation cost estimates are presented; these are based on the risk level of relocation activity required for deploying ABC. The methodology and the costs formulation can also be used to reduce the user input of cost data in Mi-ABCD. The formulations and costs presented are based on traffic data, site-specific data, and the data obtained from completed ABC projects. The costs are converted to the present value using the consumer price index converter.

Cost estimates for shallow and deep foundation types are developed and presented in this chapter. The cost estimates are provided primarily in terms of linear foot of foundation depth. Only for the spread footing, the cost is given per a cubic foot foundation. In developing the cost estimates, the historical bid-based method was implemented; this is because quantifying units of work items/activities and assigning representative unit costs for such work items/ activities was possible from the data extracted from completed ABC projects. Cost analysis was incorporated because several foundation work items/activities obtained from the completed ABC projects were measured in different units rather than linear foot of foundation. The representative costs for the cost estimates were obtained using typical factors from historical cost databases, knowledge of market conditions, and inflation rates.

The user cost and life-cycle cost (LCC) analysis for ABC are also described. Formulations are provided to calculate the user cost corresponding to the project delivery alternative. For the LCC calculations, the Net Present Value (NPV) economic analysis methodology is described. The user cost analysis considers the cost incurred by the facility carried (FC) traffic as well as the feature intersected (FI) traffic. The LCC analysis includes calculating and comparing the LCC associated with various project delivery alternatives.