Multi-Span Lateral Slide Laboratory Investigation: Phase I

Final Report
June 2021

Sponsored by
Accelerated Bridge Construction
University Transportation Center

U.S. Department of Transportation
Office of the Assistant Secretary for
Research and Technology

BRIDGE ENGINEERING CENTER
IOWA STATE UNIVERSITY
Institute for Transportation

About the ABC-UTC

The Accelerated Bridge Construction University Transportation Center (ABC-UTC) is a Tier 1 UTC sponsored by the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology (USDOT/OST-R). The mission of ABC-UTC is to reduce the societal costs of bridge construction by reducing the duration of work zones, focusing special attention on preservation, service life, construction costs, education of the profession, and development of a next-generation workforce fully equipped with ABC knowledge.

About the Bridge Engineering Center

The mission of the Bridge Engineering Center (BEC), which is part of the Institute for Transportation (InTrans) at Iowa State University, is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges. The mission of InTrans is to save lives and improve economic vitality through discovery, research innovation, outreach, and the implementation of bold ideas.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
ABC-UTC-2016-C3-ISU02-Final		

4. Title and Subtitle	5. Report Date
	June 2021
Multi-Span Lateral Slide Laboratory Investigation: Phase I	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Katelyn Freeseman (orcid.org/0000-0003-0546-3760), Zhengyu Liu (orcid.org/0000-0002-7407-0912), Justin M. Dahlberg (orcid.org/0000-0002-6184-4122), and Brent M. Phares (orcid.org/0000-0001-5894-4774)	

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Bridge Engineering Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664	11. Contract or Grant No. 69A3551747121

12. Sponsoring Organization Name and Address		13. Type of Report and Period Covered
Accelerated Bridge Construction University Transportation Center Florida International University 10555 W. Flagler Street, EC 3680 Miami, FL 33174	U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology and Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590	Final Report (January 2018–June 2021) **14. Sponsoring Agency Code**

15. Supplementary Notes

Visit https://abc-utc.fiu.edu/ for other ABC reports.

16. Abstract

Lateral slide-in bridge construction (SIBC) has gained increasing attention as a viable accelerated bridge construction (ABC) approach. With lateral slide construction, the majority of the bridge superstructure is constructed off alignment, typically parallel to the final position, and usually on a system of temporary works.

While many state departments of transportation (DOTs) have completed lateral slide construction of single-span bridges and have common connection details already established, these details do not directly apply to multi-span slides. The addition of more spans creates a more complex system that require connections (and other details) that were previously not needed in a single-span slide. In addition, the fact that the multi-span bridge needs to slide on abutments plus piers (as opposed to just abutments) creates possible uplift and overturning scenarios.

As covered in this report, a comprehensive literature search was conducted to find relevant information on the implementation of SIBC on multi-span bridges. However, limited public information was found that directly related to the substructure behavior subject to the lateral slide load. An analytical simulation was conducted to investigate the structural behavior of the bridge piers during the bridge slide-in and to evaluate the drawbacks and advantages of two- and four-point pushing.

A finite element (FE) model was developed and validated against the data collected from a field monitored bridge. The results indicated that two-point pushing increases the loading on the pier diaphragm by 36%. Because of this, the pier response with respect to the tilt about the x and z directions increased; however, this increase was not significant. By analyzing the field and analytical solution results, it was also found that the bridge pier experienced a greater rotation about the bridge transverse direction than about the longitudinal direction.

The results of the FE modeling and the literature search resulted in unanswered questions that would benefit from further study. A detailed research plan including a series of laboratory tests is proposed in the final chapter of this report.

17. Key Words	18. Distribution Statement
accelerated bridge construction—lateral slide bridges—SIBC connections—SIBC details—SIBC literature review—slide-in bridge construction	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	44	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

(this page is intentionally left blank)

Multi-Span Lateral Slide Laboratory Investigation: Phase I

Final Report

June 2021

Principal Investigator: Katelyn Freeseman
Bridge Engineering Center, Institute for Transportation
Iowa State University

Authors
Katelyn Freeseman, Zhengyu Liu, Brent M. Phares, and Justin M. Dahlberg

Sponsored by
Accelerated Bridge Construction University Transportation Center

ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

A report from
Bridge Engineering Center and Institute for Transportation
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
https://intrans.iastate.edu/

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated in the interest of information exchange. The report is funded, partially or entirely, by a grant from the U.S. Department of Transportation's University Transportation Program. However, the U.S. Government assumes no liability for the contents or use thereof.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This project was supported by the Accelerated Bridge Construction University Transportation Center (ABC-UTC at https://abc-utc.fiu.edu/) at Florida International University (FIU) as the lead institution, with Iowa State University, the University of Nevada-Reno, the University of Oklahoma, and the University of Washington as partner institutions. The authors would like to acknowledge the support of the ABC-UTC.

The research team would like to extend special appreciation to the ABC-UTC and the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology for funding this project.

This project was also made possible by match funds from the Iowa Department of Transportation (DOT) via an ongoing research project with similar project goals: *Lateral Slide of Multi-Span Bridges: Investigation of Connections and Other Details–Phase I.* The Literature Review in this report was previously published as part of that final report (Liu et al. 2021).

Thanks should also be given to the many state agency representatives that provided feedback and survey responses and participated in phone interviews to help provide the content presented in this report.

(this page is intentionally left blank)

INTRODUCTION

Background and Introduction

While single-span lateral slides have been adopted by many states and are a common accelerated bridge construction (ABC) method for construction of bridges when short closure durations are needed, multi-span lateral slides are far less common. A multi-span lateral slide incorporates additional construction complexities that must be considered by the designer, agency, and contractor.

Problem Statement

Lateral slide-in bridge construction (SIBC) has gained increasing attention as a viable ABC approach. With lateral slide construction, the majority of the bridge superstructure is constructed off alignment, typically parallel to the final position, and usually on a system of temporary works. The construction of this portion of the bridge is often completed while the original bridge is still open to traffic.

In some instances, portions of the substructure are also constructed while the original bridge is still open to traffic—a technique designed to further reduce traffic impacts. Common techniques for accomplishing this include building substructure elements outside of the original bridge footprint as well as using innovative techniques to complete construction under the bridge with consideration of clearance limitations, stability of the underlying soil, and other considerations. Once the construction of the superstructure is essentially complete, the original bridge is demolished, and the new substructure construction is completed. Then, usually over a relatively short time period (commonly hours to a day), the new bridge superstructure is slid laterally from the temporary worksite onto the in-place substructure.

While many DOTs have completed lateral slide construction of single-span bridges and have common connection details already established, these details do not directly apply to multi-span slides. The addition of more spans creates a more complex system that requires connections (and other details) that were previously not needed in a single-span slide. In addition, the fact that the multi-span bridge needs to slide on abutments plus piers (as opposed to just abutments with a single-span bridge) creates possible uplift and overturning scenarios.

Research Approach and Methods

The objectives of this project were achieved via these three tasks:

1. Literature review
2. Analytical investigation and testing plan establishment
3. Summary and recommendations for Phase 2

LITERATURE REVIEW

The objective of the literature review was to collect and summarize information relevant to SIBC. The focus of this exhaustive literature review was on published information related to lateral slide-in construction. The literature search focused on the implementation of SIBC on multi-span bridges where the lateral sliding force may induce a significant effect on the pier column, foundation, pier diaphragm, etc.

The literature search started from the *Slide-In Bridge Construction Implementation Guide* published by the Federal Highway Administration (FHWA) (UDOT and Michael Baker Corporation 2013), which provides a comprehensive introduction to the implementation of the SIBC method on bridge structures. Based on the information in this guide and the findings from other literature sources, the general SIBC procedures and characteristics were summarized.

Following that, past bridge construction cases that utilized the SIBC method since the 1990s were found from online resources, research project reports, and technical articles. These resources were reviewed with the results presented. By reviewing these SIBC projects, the research team gained a comprehensive understanding of the current status of the implementation of SIBC on multi-span bridges.

During this process, the cases that may be related to SIBC of multi-span bridges and the study of pier/foundation behavior during the slide were identified. Another round of literature search and review was conducted to find detailed information or research activities for SIBC cases that may contribute to the final objective in this research project.

SIBC Procedure

Sliding a constructed bridge is not a new concept and has been successfully implemented in many projects nationwide. The Utah Department of Transportation (UDOT) and Michael Baker Corporation (2013) developed the *Slide-In Bridge Construction Implementation Guide* for the FHWA to demonstrate the advantages of SIBC and document how state and local agencies can implement SIBC in typical bridge replacements as a part of their standard business practices.

The authors pointed out that, most often, these projects have been large bridges with high traffic volumes that limited other construction options. The application of SIBC on smaller, routine bridges is relatively new and underutilized. However, state agencies and the FHWA have successfully employed SIBC with small bridge replacements as an innovative option to minimize impacts to the traveling public.

SIBC offers a cost-effective technique to rapidly replace an existing bridge while reducing impacts to mobility and safety. Usually, implementation of SIBC involves the following procedures:

1. Construct a temporary substructure next to the existing bridge as the support for the superstructure of the new bridge.
2. Construct the superstructure on top of the temporary substructure while maintaining traffic on the existing bridge.
3. Construct the substructure under the existing bridge without disturbing traffic.
4. Detour traffic to the new bridge superstructure built on the temporary support and demolish the existing bridge. (The construction of the new substructure sometimes continues during this step.)
5. Slide the new bridge superstructure onto the new substructure. The road closure for the sliding usually takes a few hours to several days.

SIBC Applications

The researchers identified more than 40 projects in the past 30 years that have used the slide-in method for single- or multi-span bridges from online webpages, research project reports, and technical articles. The researchers reviewed the information on these to gain a full understanding of the current implementation status of SIBC.

Since the objective of the research focus was on multi-span bridges, with an emphasis on the pier region, only those cases that used SIBC on multi-span bridges are summarized in this section. A summary of the details for these 10 multi-span bridges is provided in Table 1.

Table 1. Multi-span bridges constructed using SIBC approach

No	Bridge location	Year	State	Original bridge			New bridge								
				Total span #	Total length (ft)	Total width (ft)	Total span #	Total length (ft)	Total width (ft)	Max. # of spans (each slide)	Beam type	Pier type	Foundation type	Diaphragm type	Sliding system
1	I-405 over Northeast 8th Street Bridge	2003	Washington	6	293	103	2	328	121.5	2	Steel I-girders	Beam column frame	Spread footings	Steel	Roller
2	Hood Canal Bridge	2005	Washington	6	643	30	5	605	40	5	Prestressed bulb tee girders	Beam column frame	Drilled shafts	Concrete	Rollers
3	Elk Creek Bridge	2008	Oregon	6	340	30	3	320.5	38.2	3	Steel I-girders	Beam column frame	Drilled shafts		Bearing pad
4	Ben Sawyer Swing Bridge	2010	South Carolina	>3			>3	1,154	36.5	6	Steel plate girders	Beam column frame (reused)		Steel	
5	I-44 over Gasconade River	2011	Missouri	6	670	34	6	670	36.67	4	Steel plate girders	Beam column frame		Steel	Stainless steel and Teflon sliding surface
6	Sellwood Bridge	2013	Oregon	4	1100					4	Steel Truss				
7	I-84 over Dingle Ridge Road	2013	New York		140	33.3	3	140		3	Double Tee NEXT beams				
8	Larpenteur Avenue Bridge	2014	Minnesota		185.5	61	2	187	75.8	2	Prestressed concrete beams			Concrete	
9	M-50 over I-96	2014	Michigan	4	227	37.5	2	198	71.25	2					
10	Poplar Street Bridge	2018	Missouri	5	2165							Beam column frame (reused)			

The information in Table 1 indicates that most of the bridges have two to six spans and that the whole bridge was built continuously over the piers and slid simultaneously onto the permanent structure. These construction projects include I-405 over the Northeast 8th Street Bridge, the Hood Canal Bridge, and others.

For the bridges with tens of spans and usually constructed over a river, the superstructure was usually divided into units of up to three spans, and each unit was slid into final position using the SIBC approach (sometimes in conjunction with the float-in method). For example, the Ben Sawyer Bridge slid the six approach spans on each end and floated in the steel truss span in the middle.

By comparing the lengths of the new bridges to that of their original bridges, the researchers found that the total length of the new bridges is usually shorter than that of the original bridge, such as the Hood Canal Bridge and the Elk Creek Bridge. This observation shows good agreement with the findings from UDOT and Michael Baker Corporation (2013), where it was shown that the SIBC method required the construction of the substructure for the new bridge under the original bridge without disturbing the traffic on the old bridge. The common practice to achieve that is to build the new abutment in front of the original one. The new bridge is usually wider than the original bridge due to increased traffic volume.

The information in Table 1 also indicates that the beam-column frame pier is the most frequently used pier type for construction of the multi-span bridge utilizing the SIBC approach. During the review of the literature, no special consideration seemed to be given to the pier design. And, no issues have been reported for the use of the beam column frame associated with the SIBC method.

With respect to the foundation type, the limited information indicated that both spread footings and drilled shafts were used.

The selection of the material for the diaphragm is mostly based on the type of girder. Both steel and concrete diaphragms were used with the SIBC approach without reports of an issue.

For the selection of the sliding system, it appears when the superstructure in each slide exceeds approximately 300 ft in length or 50 ft in width, the roller support was commonly used, since a large heavier superstructure requires a low coefficient of friction on the sliding track to reduce the lateral sliding force demand.

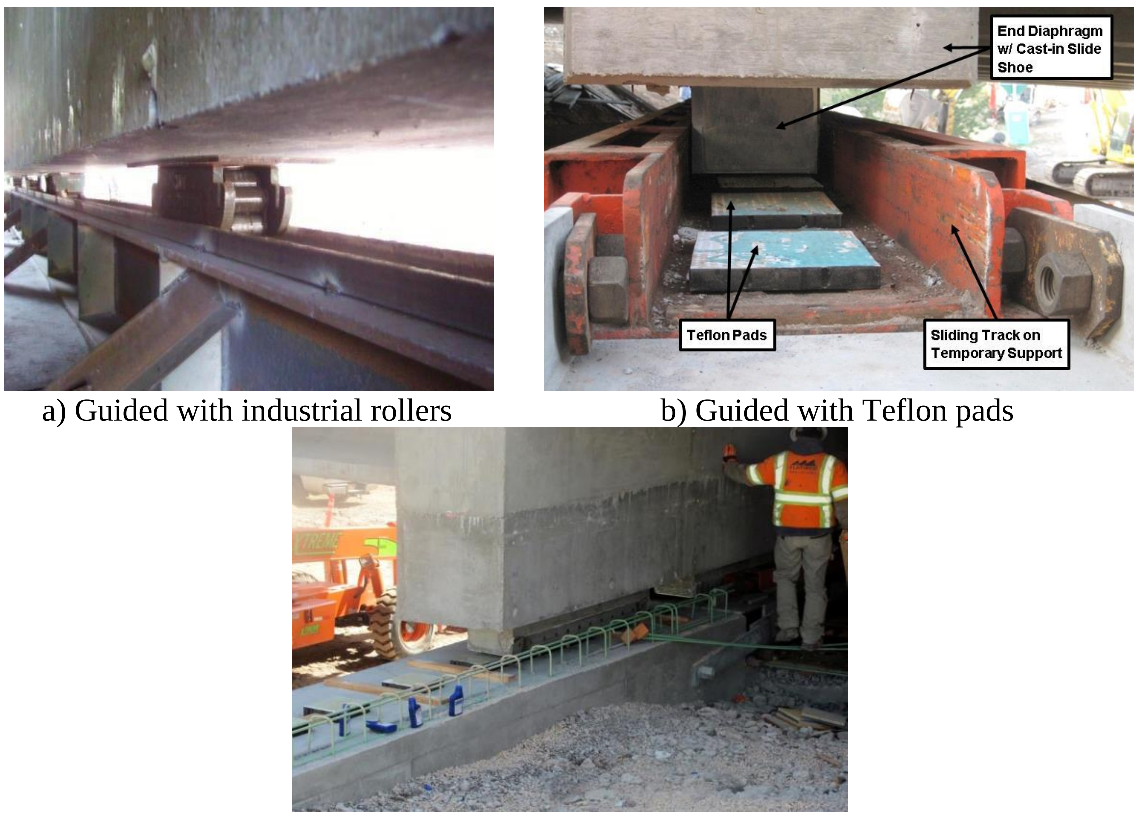
The researchers found that both steel plate girders and prestressed concrete beams were used for multi-span SIBC.

SIBC Equipment and Techniques

Compared to conventional construction methods, SIBC requires the use of additional equipment to move the new superstructure from the temporary supports to the permanent ones. The special equipment used for SIBC usually includes a sliding system with rollers or bearing pads as the contact between the substructure and the superstructure, an actuating system (sometimes used with a movement control mechanism) to provide the power for the movement, and one or two temporary structures used to support the new or old superstructure. In this section, different types of equipment used during the slide-in procedure are discussed with respect to their effect on the substructure of the multi-span bridge.

Sliding Systems

Sliding systems provide and maintain a path for the superstructure during the lateral slide. Polytetrafluoroethylene (commonly known as Teflon) pads and rollers (shown in Figure 1) are most commonly used for the slide systems in SIBC.



a) Guided with industrial rollers

b) Guided with Teflon pads

c) Unguided with Teflon pads

UDOT and Michael Baker Corporation 2013, FHWA

Figure 1. Sliding systems

Industrial rollers are usually installed under the girders or end diaphragm of the new bridge and used with a sliding track. The sliding track maintains the movement in the slide direction. One of the advantages of using rollers is that, compared to the Teflon pad, sliding friction is very low in roller systems. The coefficient of friction of the roller system is usually less than 5% and the breakaway friction is close to the kinetic friction since the sliding velocity is very low. The low friction of coefficient means less external force is needed to initiate and keep the movement of the superstructure and, as a result, the reaction force on the temporary and permanent substructure is low.

UDOT and Michael Baker Corporation (2013) list a few major drawbacks on roller systems, including that the large point load occurs under each roller, binding or jamming of rollers may occur if not aligned properly, and start and stop ability should be provided during the slide since the dynamic coefficient of friction is low. The large point load requires more attention on the design of permanent and temporary substructures. In addition, vertical jacking is required to remove the rollers after the superstructure is moved to its final position.

Teflon pads are the most commonly used sliding system in SIBC approaches. This method uses elastomeric or cotton duck bearing pads topped with Teflon to slide the bridge into place. The pads are usually lined along the temporary supports and permanent substructures, and the bottom of the bridge diaphragm becomes the sliding surface. Slide shoes or sliding blocks can be cast into the diaphragm and wrapped with a sliding surface such as stainless steel. With this method, the final sliding pads on which the bridge stops can be left in place to act as the final bearings.

Aktan and Attanayake (2015) indicated that the coefficient of friction associated with Teflon pads could be as much as 20%. The Bridge Engineering Center (BEC) research team at Iowa State University tested the behavior of the bearing pads to determine if excessive shear deformation occurs such that the bearing pads may “roll” during construction. The results indicated that the coefficient of friction was calculated to be approximately 0.11 for the non-lubricated tests and 0.07 for the lubricated tests. For the multi-span bridge, a greater friction coefficient may result in a larger reaction force to the pier column and the foundation structures.

There is no best system for any specific application (UDOT and Michael Baker Corportation 2013). Geometry, weight, tolerances, and experience are the parameters considered in the selection of slide systems. Sliding resistance of Teflon pads is relatively greater compared to rollers, resulting in a greater reaction force on the substructure. Parameters that affect Teflon-steel interface friction include sliding velocity, normal pressure, Teflon composition, steel sliding surface roughness, surface treatment (lubricant applied at the interface), temperature, and the angle between the surface polishing of steel and the slide direction (Hwang et al. 1990).

Ridvanoglu (2016) divided the sliding system into two categories: **guided and unguided systems**. Guided systems include restraints in the transverse direction to limit movement in the direction perpendicular to the slide. Unguided systems provide no transverse restraints. Both Teflon pads and rollers can be utilized in conjunction with guides (tracks) to provide smooth sliding with restraints to transverse movement, but the use of Teflon pads alone cannot provide any transverse restraints and belong to the unguided system.

On multi-span bridges, guided systems over the pier could prevent drifting of the superstructure, but may result in binding due to a development of large transverse forces. This can possibly damage the pier since it is generally not designed for transverse forces. On the other hand, unguided systems could prevent force development in the transverse direction, while excessive drifts may result in loss of alignment.

These undesirable situations in guided and unguided systems are generally inevitable because of the uncertainty of sliding resistance. Ridvanoglu (2016) pointed out that transverse forces should be considered in the design of the temporary and/or permanent substructure in the uses of guided systems.

Actuating Devices

Actuating systems are used to provide force to initiate and maintain the slide. Sliding can be completed by pushing, pulling, or the combination of both. Most commonly used actuating systems include hydraulic rams, mechanical pulling devices, and prestressing jacks. To provide enough force for the slide, multiple actuating devices placed at different locations are usually required.

Ridvanoglu (2016) indicated that the difference between the applied force and resistance is not constant throughout the slide-in. This may result in binding on one side, with uncontrollable drifting of the superstructure.

Hydraulic jacks are usually installed along with Teflon pads and a sliding track system to provide an anchor to push against and guide the bridge to its final alignment (see Figure 2-a).

a) Hydraulic jacks b) Mechanical pulling devices c) Post-tensioned jacks

UDOT and Michael Baker Corporation 2013, FHWA

Figure 2. Actuating devices

To execute the slide, the jacks extend to full stroke to push the bridge forward while anchoring against the slide tracks or temporary supports. On a multi-span bridge, the hydraulic cylinders are usually connected to superstructure diaphragms over the abutments and piers, and cylinders are capable of pulling and pushing.

Ridvanoglu (2016) indicated that capacity and stroke length of the hydraulic cylinders are important for the slide, especially to prevent binding. Binding may result in damage to the superstructure in the use of longer stroke-length cylinders if the binding occurs in the beginning of the push cycle.

Mechanical pulling devices, such as a winch or crane, can pull the superstructure along rollers or Teflon pads to its final position (see Figure 2-b). Separate pulling devices can be used at each pulling location, or a system of pulleys can be used to allow one mechanical pulling device to pull simultaneously on multiple points. If using one pulling device with a pulley system, the bridge is uniformly moved on all pull points.

One of the major drawbacks of mechanical pulling devices pointed out by UDOT and Michael Baker Corporation (2013) is that there is no ability to "back up" the pull without a separate pull system set up on the opposite side of the structure. Consequently, the system is usually used along with hydraulic jacks.

Post-tensioned jacks are small jacks used to pull an anchored post-tensioned strand or threaded high-strength bar and push the bridge into place on rollers or Teflon pads (see Figure 2-c). UDOT and Michael Baker Corporation (2013) pointed out that it requires abutment or diaphragm designs that allow anchoring of the post-tensioned strands and transfer from a pulling force on the strand to a pushing force on the superstructure, and there is no ability to "back up" the pull without a separate pull system set up on the opposite side of the structure.

Ridvanoglu (2016) indicated that these systems are generally used with a pulling operation since jacks can only apply tensile forces. In addition, cable systems do not require settling for each pulling cycle. UDOT and Michael Baker Corportation (2013) indicated that the cable flexibility and prestressing losses could generate jerks in movement.

Movement Control Mechanisms

Two approaches are used to control movement during the slide: pressure-regulated systems and servo-controlled systems. Pressure-regulated systems are used more commonly than servo-controlled ones.

Pressure-regulated systems are capable of controlling only the hydraulic pressure applied to a jack. Combined pulling and pushing methods are utilized multiple times. Pressure-regulated systems should only be used with guided slide systems, along with attentive visual monitoring of movement and a contingency plan.

While most cases require force applications that result in equal displacements of supports, it is possible to slide the structure to a skewed position along a curved path of travel. The Sellwood Bridge move in Oregon required a final position at a skew, with a total translation of 66 ft and 33 ft for the west and east ends of the structure, respectively. The truss structure moved along a curved path due to the skewed alignment and thus, the steel translation beams were designed to account for the curve. The move was accomplished using a "digitally-controlled power pack" that regulated the amount of fluid going to each jack. Jacks at the west end were regulated to push twice as fast as the jacks on the east end, with jacks between end supports pushing at proportional rates.

Ridvanoglu (2016) indicated that pressure-regulated actuating faces a differential friction result with drifting of the superstructure. This event may be prevented by monitoring and/or using a short stroke-length cylinder.

Servo-controlled systems monitor displacements and calibrate applied pressure automatically to balance the movement. A servo controller can be utilized to monitor real-time displacement in different rails in order to control an equal sliding rate. Drifting delays the slide and increases the duration of the slide-in (Ridvanoglu 2016).

Pressure in each abutment or bent is synchronized and automatically corrected to ensure equal displacements. Servo-controlled systems maintain an aligned slide-in given the difference in friction resistance is balanced with controlling the applied pressure. Servo-controlled systems should be utilized with unguided slide systems to eliminate the effects of differential friction resistance.

Aktan and Attanayake (2015) indicated that the control of forces using the pressure control valves at the manifold is often quite slow. To allow accurate and rapid force control during the move operation, a servo controller is required. The inclusion of the servo controller requires the use of electronics and most likely a field computer.

On a multi-span bridge where more than two actuating devices are used for each slide, multiple controllers can be synchronized to achieve equal force or displacement and reduce the possibility that binding occurs; as a result, it reduce the chance of damage to the superstructure, substructure, and actuating devices.

Locations of Force Application

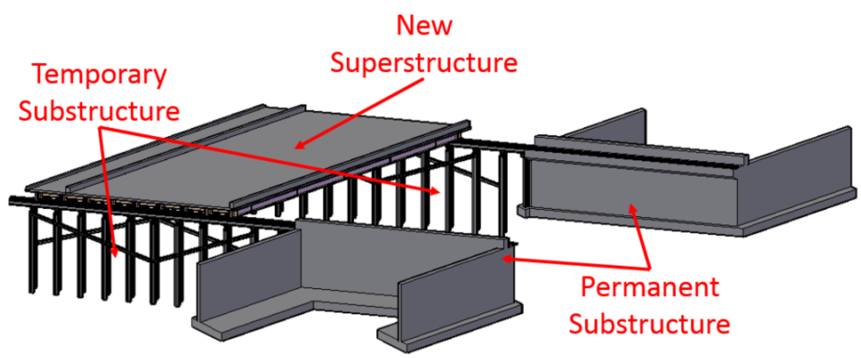
Most of the bridges constructed in the US utilizing the SIBC approach have been single-span bridges. However, the SIBC approach has been successfully used to move up to six-span superstructures. The superstructure of bridges with more than six spans are usually divided and pre-fabricated as six-span units and slid in individually. For single-span bridges, it is a common practice to place an actuating device at each abutment. For bridges with more than one span, the actuating devices have usually been placed at both the abutment and the pier diaphragms. However, coordination of separate mechanical systems is required at each push/pull location to perform a smooth slide-in.

Temporary Structures

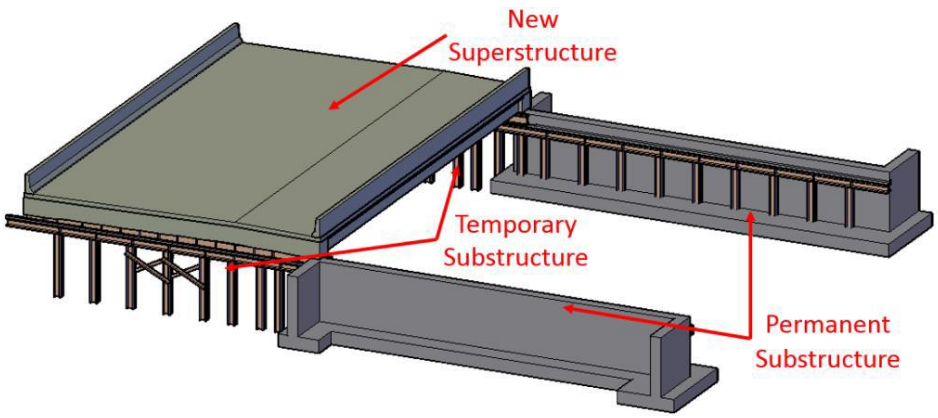
To slide a multi-span superstructure using the SIBC method, temporary support structures are required at the pier location before and during the lateral slide. Temporary structures include a foundation, a frame system, and a sliding track. Loads transferred to temporary supports by friction forces need to be considered as well as gravity loads, such as weight, traffic, and equipment, in the design.

Another consideration to take into account with temporary structures is their use is not only limited to the bent for the new superstructure but can serve as a bent for the old superstructure. In the Oregon DOT's Elk Crossing bridge project in 2008, a temporary bent was used on either side of the existing structure to construct the new superstructure, and to quickly remove the existing superstructure. The existing bridge was freed and jacked laterally onto temporary supports, with the new superstructure being jacked laterally into alignment afterward. This method saved the need for full demolition to clear the alignment for the new superstructure and reduced closure time for the single structure to one weekend.

UDOT and Michael Baker Corporation (2013) indicated that defining the load path for the sliding forces is an important step when designing temporary supports. Force development in the transverse direction of the slide is generally disregarded in the design, yet field observations and slide monitoring studies show that forces develop in the transverse direction. Ridvanoglu (2016) classified temporary structures into two categories: inline and in-front temporary structures. **Inline temporary structures** resist superstructure loads during construction and the initial stage of the slide (see Figure 3-a).



a) Inline temporary structure



b) In-front temporary structure
Ridvanoglu 2016, Western Michigan University

Figure 3. Temporary structures

An inline support is connected to the permanent structure, and sliding is maintained from temporary supports to the permanent substructure. Design and construction of the connection between the temporary and permanent substructure has significant importance to assure a smooth transition during the slide. Axial forces, shear forces, and moments can be transferred through the connection when the temporary support is continuous. Bolts are the most common devices to provide continuity of the connection. Continuous connections are most favorable since they provide a smoother path for sliding and minimize temporary support-related binding problems.

Cold joints, hinges, and solid grout are used and classified as semi-continuous connections. Semi-continuous connections limit load transfer in some directions. A discontinuous connection is not recommended since it may result in differential deflections at the connection, which prevents a smooth transition resulting in an increase in slide resistance. Development of a large point load is possible just before crossing from temporary supports to a permanent substructure, which can result in a deflection difference creating slide obstacles.

An important lesson learned from the I-44 over the Gasconade River Bridge was to cast or erect the temporary bent such that it has a constant elevation across the top. This facilitates an easier process with sliding the structure, but typically requires a minor modification to the original bridge design. Typically, the bridge crown is achieved through a stepped cap on the pier, but this would obviously hinder any slide efforts. Therefore, to achieve a flat sliding surface, the crown can be created by thickening each bearing plate the same amount as any removed step. This allows the bottom of bearings to be at a constant elevation and facilitates a slide regardless of the deck crown.

However, if constant temporary or permanent bent elevations are not possible, SIBC can still be completed even on a slightly sloped structure, as seen in the 2003 I-405 NE 8th Street Bridge slide. The structure was slid in two halves split down the length of the structure and formed a crown in the roadway cross-section of 2%, where the slopes of the temporary or permanent cap beams were sloped to match. Even with each half coming in at 4,400 kips, through the use of an innovative slide system at the time, the structure was successfully rolled up the 2% grade.

In-front temporary structures include construction of a temporary support system for the full slide-in operation (Figure 3-b). A lateral slide is operated on a temporary structure, and transfer to the permanent substructure is performed after the slide for the permanent alignment. This system requires vertical lifting after the slide to place the superstructure in its permanent location. In addition to general considerations, eccentric loads can develop on the permanent substructure when an in-front temporary support system is utilized. Using the foundation of the permanent abutment to support the temporary support system and the connecting rail girder to the abutment cap in the permanent location has been documented for past projects. However, no record indicated that this type of temporary system has been used at a pier location.

Foundation selection for the temporary support generally depends on the soil conditions. Driven piles, drilled shafts, micro-piles, or spread footings can be used. The foundation of the permanent piers can also be used as a foundation for temporary supports in specific applications.

Ridvanoglu (2016) pointed out that the settlement and deflection of the system subject to the full bridge load should be calculated in order to determine the elevation to initially set the temporary support. It is also recommended that a moving load analysis be performed for the temporary support system considering forces developed in the direction of gravity, the slide-in, and the transverse of the slide-in. Furthermore, if traffic is shifted to the new superstructure while on the temporary structures, a traffic live load analysis should be performed.

Design Considerations for Permanent Substructures

The design considerations discussed in this section focus on the permanent substructure, foundation solution, and diaphragm type. The foundation solution was studied for a permanent pier in this section.

Special Considerations

The slide-in process in the SIBC approach has special requirements on the design and construction of the substructure near the pier. The most commonly experienced challenges for the selection and construction of substructures include the large horizontal loading induced by the slide-in process, influence of the new foundation on the existing substructure, and limited headroom.

The first challenge to overcome is the **large horizontal loading** during the slide-in process. The magnitude of the force required to initiate and maintain the movement of the superstructure depends on the weight of the superstructure and the coefficient of friction between the superstructure and the substructure.

Aktan and Attanayake (2015) indicated that the weight of the superstructure to be moved is generally in excess of one million pounds, so the force required to initiate the motion will be about a half million pounds. Usually, the design of bridge foundations do not consider the large horizontal forces induced by ABC implementations such as SIBC due to pull or push mechanisms. Hence, it is essential to evaluate the capacity of the substructure and foundation before the slide-in.

If the foundation lacks the required lateral load capacity, temporary bracings can be designed to support the substructure and foundation. For the pier structure, the challenge can be overcome by using the in-front temporary structure or through reinforced design of the substructure.

The second challenge to overcome is the **influence of the new foundation on the existing foundation** since, most of the time, the SIBC approach requires construction of the new foundation next to the original foundation, and the fill must be excavated and retained against the existing foundation.

Aktan and Attanayake (2015) indicated 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. The dynamic effect of installing a new foundation adjacent to an in-service bridge is also a consideration in SIBC projects. To overcome this challenge, spread footing foundations, drilled shafts, auger piles, and micro-piles with proper installation methods are recommended.

The effect of vibrations on the old foundation due to pile installation should also be considered. Zekkos et al. (2013) developed a tool to estimate ground vibration 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.

Finally, during foundation installation, the existing bridge response needs to be monitored to assure its stability.

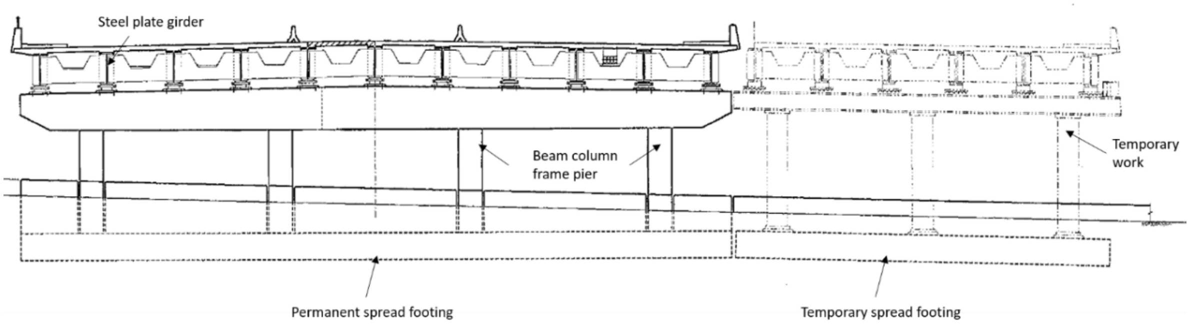
Usually, the SIBC approach requires the construction of the substructure underneath the existing structure when traffic remains open on the existing structure. The **headroom limits** the construction of the foundation and use of various equipment. This challenge can be overcome by both design and the construction method. UDOT and Michael Baker Corporation (2013) indicate that it is a common practice to design the new bridge with a shorter span length than the existing bridge, which enables the new abutments to be constructed underneath the existing bridge prior to its demolition.

For the pier, a straddle bent can be used to install foundations outside the existing bridge footprint. The bent is designed to span between the two foundations. When using a straddle system, deflection of the spanning element (seat) during the slide and in the final configuration should be considered. In addition to using typical columns and bent caps, hammerhead piers and piers with two outriggers, precast posttensioned segmental piers, and prestressed or posttensioned bent caps are also options for SIBC projects.

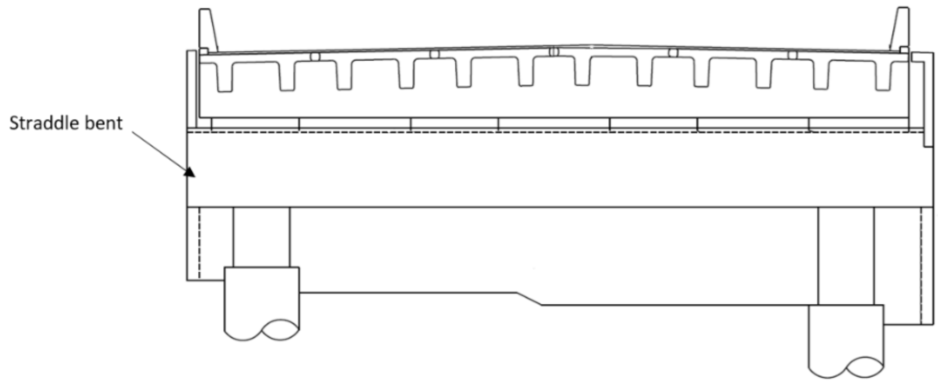
Foundation Solutions

Phares et al. (2019) studied the available foundation types for construction under existing bridges. The use of shallow foundations, drilled shafts, and micro-piles were recommended. Furthermore, supported excavation is recommended to assure the structural stability of the in-service bridge.

Spread footings are the simplest and most cost effective foundation alternative when soil conditions permit. Spread footings do not require excessive headroom during construction, and performance is the same as that with a traditional construction project. Figure 4-a shows the plan for the beam-column frame pier built on spread footings for the I-405 Bridge over NE 8th Street in Washington.



a) Beam-column frame pier on spread footing (I-405 over NE 8th Street, Washington)



b) Drilled shaft (I-84 bridge, New York)

Figure 4. Substructure type

Drilled shafts are another alternative for the new bridge foundation, as shown in Figure 4-b for the I-84 bridge in New York. Note that the construction quality of drilled shafts with unsupported excavations could be a concern. Supported excavation for drilled shafts can assure the stability of the in-service bridge as well as foundation construction quality. Crosshole sonic logging 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.

Micro-piles can be used when deep foundations are required and traditional piles cannot be driven under the existing bridge due to limited vertical clearance. A micro-pile is a small diameter pile (typically less than 12 in.) that is drilled and grouted. Micro-piles can be used in areas with low headroom due to their smaller size and segmental installation, which allow the use of smaller equipment. A new bent with micro-piles constructed near an existing foundation must avoid conflicts with any existing battered piles. Since micro-pile cross-sectional areas are smaller compared to other deep foundation systems, the buckling and lateral load capacities could be a concern.

An additional solution for deep foundations is to core through the existing deck and drive the piles through holes in the deck. This method allows for typical pile arrangements and minimizes quantities. The primary concerns are traffic control with additional impacts to traffic, covering or patching of the core holes, and the potential to damage existing girders. A review of past construction documentation indicated that micro-piles have not yet been utilized underneath the pier on a multi-span bridge constructed utilizing the SIBC approach.

Sometimes, the existing foundation can be reused for the new structure. However, only one project report was found where the existing foundation was reused. This is because the new bridge footprints are usually different from that for existing bridges. If the new bridge is on the same or partially on the same footprint, foundation reuse potential or replacement can be evaluated. 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. Assessment of an unknown foundation requires a detailed investigation to collect the necessary data.

The Illinois DOT (IDOT 2011) developed a comprehensive procedure and guidelines for foundation reuse. According to that, the existing substructure and foundation elements are assumed to have adequate load capacity for reuse without a detailed structural analysis when the following conditions are satisfied:

- The substructure elements are in good condition (National Bridge Inventory [NBI] condition rating of 6 or higher) and show no significant structural distress under existing live loads
- 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)

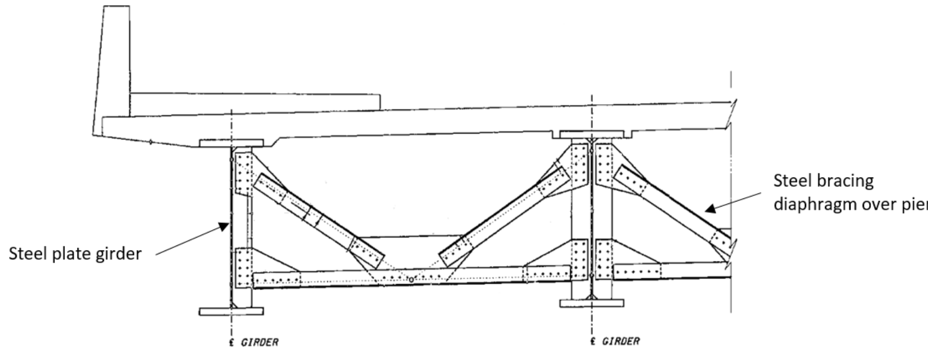
Diaphragm Types

A detailed literature search on the use of different diaphragm types over the pier for SIBC projects was conducted; however, little relevant information was found. More information related to the end diaphragm was found, which might give some hints on the design of the diaphragm over the pier.

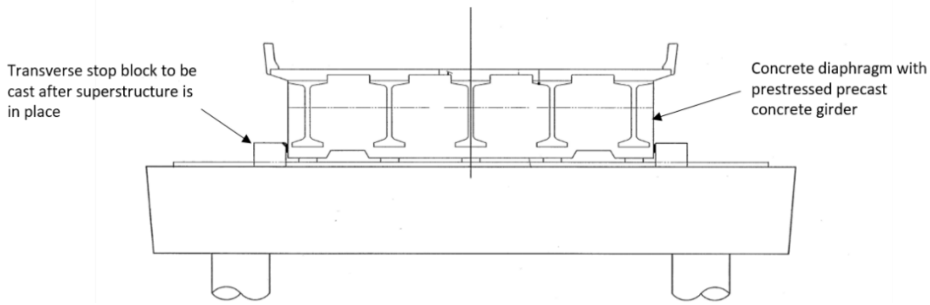
For example, UDOT and Michael Baker Corporation (2013) indicated that the solid end diaphragm on semi-integral abutments provides a large, rigid member to jack up the bridge and mount the various sliding systems. The continuous diaphragm allows rollers or sliding shoes anywhere along the abutment (not just underneath the girders). Avoiding bearing points in the center of the abutment beam can minimize permanent moment loads and deflections. In addition, excessive deflections of the seat can cause sliding supports on the end diaphragm to lose contact with the abutment seat and require the end diaphragm to span between two adjacent sliding supports that still have contact. One solution to this is to design the end diaphragm to span over one slide support that loses contact. Another solution is to design the end diaphragm stiffness to allow flexibility and redistribution of the load as the seat deflects.

A review of bridge plans indicated that both steel bracing diaphragms and concrete diaphragms have been successfully used for steel plate girder bridges. The I-405 bridge over NE 8th Street in

Washington utilized steel bracing diaphragms over the pier, as shown in Figure 5-a, while the Hood Canal Bridge, also in Washington, used concrete diaphragms, as shown in Figure 5-b.



a) Steel diaphragm (I-405 over NE 8th Street, Washington)



b) Concrete diaphragm (Hood Canal Bridge, Washington)

Figure 5. Diaphragm type

On the I-44 Bridge over the Gasconade River slide, steel W-shaped diaphragms were used for the end and pier diaphragms. Originally designed for conventional construction, these items required design modifications to meet the needs of the SIBC system. The diaphragms had to transfer the pushing loads into the superstructure more effectively and were redesigned accordingly. Bearing stiffeners and connection plates outside the diaphragm provided the connections to the jacks for lateral movement. Additionally, due to clearance limitations, the diaphragms were designed to handle the vertical jacking loads necessary for the transitions of the bearings. These two design modifications showcase the need for special considerations regarding the bridge diaphragms when using SIBC.

While some modifications are necessary, it was noted that these were the only design modifications required for the structural steel due to the SIBC method. Lastly, it was also noted that the flexibility of the steel superstructure was prevalent in ensuring no damage or cracking occurred from moving the structure into place.

Another design detail to consider from the New York State DOT’s (NYSDOT’s) I-84 Bridge over Dingle Ridge Road is the use of diaphragms as the sliding surface rather than the beam bearings. This bridge was comprised of precast NEXT beams that sat on a prefabricated rigid diaphragm outfitted with four slide shoes. The design was done this way to avoid conflict with other structures onsite.

Research Investigations for SIBC

Although SIBC has been used for decades, few research activities have been conducted to study the structural performance during the slide-in. The research team found that two approaches have been used to investigate the performance of structures during the lateral slide: field monitoring and finite element simulation.

Field Monitoring During SIBC

Most of the SIBC projects were monitored with **conventional monitoring** tools to ensure successful completion of the project. UDOT and Michael Baker Corporation (2013) recommended use of a conventional monitoring plan in each SIBC project to control horizontal and vertical alignment of the bridge superstructure during the bridge slide-in. They suggested monitoring superstructure rotation around the longitudinal and transverse axes by measuring elevation or by using other methods approved by the project engineer. The authors also suggested observation and reporting of excessive deflections, twist, and change in longitudinal and transverse gradients.

Ridvanoglu et al. (2017) suggested including a monitoring plan regardless of the selected structural system for construction. The report suggests using an actuating system under displacement control that utilizes synchronized self-monitoring systems to control superstructure movement and maintain the move at a steady rate. Typically, a conventional monitoring plan includes monitoring the hydraulic manifold pressure and displacements in the direction of the slide and transverse to the slide.

Shutt (2013a, b, and c) indicated that in order to prevent drift, displacement in both actuating systems should be monitored during the slide. Uneven movements are frequent, and monitoring the displacement is essential for early corrections, which may prevent misalignments. Displacements are usually monitored using measuring tapes, total stations, or servo-controlled monitoring systems. Hydraulic manifold pressure is measured using pressure gauges, load cells attached to actuators, or computerized servo-controlled monitoring systems.

In addition to conventional monitoring of the slide-in process, SIBC projects have been conducted **monitoring for specific interests**. Akant and Attanayake (2015) performed field monitoring to investigate abutment movement when the old superstructure was demolished. An automated robot with six targets was installed on each abutment wall and used for monitoring. The robot was programmed to measure the displacements of the abutment walls continuously and report any readings that exceeded the tolerances.

The Michigan US 131 over 3-Mile Road bridge slide-in monitored railing girder and deck displacements using nine targets on the deck and seven targets on each railing girder. During the pulling operation, the pressure was kept equal on both jacks and adjusted manually as needed.

Pier displacements were monitored during the slide of a four-span bridge on M-50 over I-96, in Michigan. During the bridge slide, the pier was instrumented with targets, and the movement was measured with non-contact laser equipment. The targets were mounted on the bent cap and the columns. The laser tracker was located with a view of all targets, but about 150 ft away from the targets. The displacement data measured during monitoring were used to calculate forces applied to the pier during the slide in all three directions.

Ridvanoglu et al. (2017) monitored the slide-in process of the M-100 bridge over the Canadian National (CN) Railway in Michigan to capture the superstructure rocking during the slide-in. Two accelerometers (one in the direction of the slide and the other in the direction perpendicular to the slide) were mounted on the bridge deck. The bridge slide was performed with a series of discrete push cycles. Data acquisition during each cycle was synchronized by visually observing and recording the start and end of each event. Acceleration response of the superstructure was recorded throughout each slide event. Substructure and actuating system design forces were estimated from the assumed friction coefficient of the sliding surfaces.

The researchers concluded that acceleration monitoring is sufficient in quantifying transverse forces and the differential friction developed between tracks during the slide of a simple-span superstructure. Measuring acceleration in multiple directions at a single location is also sufficient for calculating friction differences between sliding tracks for a single span. The results indicated that the large difference in the friction coefficient between tracks created rocking of the superstructure and generated transverse force applied to the temporary structure. The differential friction coefficient of 1.09% between the two tracks generated a transverse force of 0.63% of the superstructure weight.

Finite Element Simulation for SIBC

Ridvanoglu (2016) developed finite element models using ABAQUS/Explicit to study the influence of different sliding and actuating system on structural behavior. Two completed SIBC projects in Michigan were used as the prototype for simulation development.

The first model described the lateral bridge slide of the US 131 Bridge over 3-Mile Road. This model's simulations included unguided and guided sliding systems with Teflon pads, pressure-regulated and servo-controlled actuation systems with a pulling method, and an in-front temporary sliding support structure.

The second model described the lateral bridge slide of the M-100 Bridge over the Canadian National (CN) Railway. Simulations on this model included a guided sliding system with rollers, a pressure-regulated actuating system with a pushing method, and an inline type of temporary sliding support structure.

Simulation results were analyzed to identify sources of the observed challenges and to verify and quantify completed SIBC project outcomes. Ridvanoglu (2016) found that simulation results are useful in identifying the time histories of forces possibly developed on the sliding surface and at the base of temporary structures. Displacements of temporary structures were also calculated through simulations.

Literature Review Summary

A comprehensive literature search was conducted to find relevant information on the implementation of SIBC on multi-span bridges. However, limited public information was found that directly related to the substructure behavior subject to the lateral slide load. One of the reasons is that not many research activities have been conducted to investigate the substructure response during the slide. Another reason is that some methods and practices have never been documented with published details.

Based on conversations with the TAC members during the meetings in June and August 2019, the research team learned that the Iowa DOT was looking forward to build a multi-span bridge using the SIBC method. The details of this bridge had not been decided by the date of drafting this report. As one of the objectives of this project, the results from the literature review and survey were expected to offer some immediately implementable design recommendations for the upcoming project.

Based on the results from the literature review and survey, the following conclusions can be made with regard to the practical and usable design guidance:

- For most of the bridges with two to five spans, the whole superstructure was usually built continuously over the piers and slid simultaneously onto the permanent structure. For bridges with more than six spans, the superstructure was usually divided into units of up to a few spans, and then slid into final position using the SIBC approach. The investigation indicates that the maximum number of spans in each slide that has been performed is six.

- The length of the bridge superstructure that was built utilizing SIBC method could be as long as 2,165 ft. It was found that the total length of the new bridge was usually shorter than the original bridge since the SIBC method required the construction of the substructure for the new bridge under the original bridge without disturbing traffic on the original bridge. The common practice to achieve that is to build the new abutment in front of the original one. The new bridge is usually wider than the original bridge due to the increase in traffic volume.

- Both spread footings and drilled shafts were commonly used for the foundation. The most frequently used substructure type is the beam-column frame pier with a spread footing foundation, although drilled shafts and driven piles were also used. The most commonly experienced challenges for the selection and construction of substructures include limited headroom, influence to the existing substructure, and the large horizontal loading induced by the slide-in process. During foundation installation, the existing bridge response needs to be monitored to assure its stability.

- With respect to the bridge girders, both pre-stressed concrete beam and steel plate girders have been used with SIBC. However, no special consideration for the lateral flexural stress level in continuous girders has been given to the design of the girders in the past. Both steel and concrete diaphragms were used with the SIBC approach without report of an issue. In general, the lateral forces were applied at all of the diaphragms over the abutment and pier. The diaphragms are expected to be designed as a large, rigid member to jack up the bridge; transfer the lateral load to the deck and girders, and place the rollers and sliding shoes in multiple locations to prevent load concentrations.

- Both Teflon pad and roller systems have been used with multi-span bridges. For selection of the sliding system, it appears that, when the superstructure for each slide exceeds about 300 ft in length or 50 ft in width, the roller support was commonly used, since a large, heavier superstructure requires a low coefficient of friction on the sliding track to reduce the lateral slide-in force demand. The researchers found that the coefficient of friction for the Teflon pads were usually assumed from 7% to 20%, while, for the roller system, the friction usually assumed was less than 5%.

- Both steel and concrete temporary structures have been used with inline setup. No outline setup had been used for a multi-span bridge. The inline setup slides the superstructure from the temporary structure directly to the permanent structure. Hence, the connection between the temporary and permanent structure is critical. The different settlement between the permanent and temporary structure during the slide-in of the superstructure is usually a concern. A common practice to capture it is to perform a trial slide before the full slide-in to measure the different settlement. It was suggested that the settlement and deflection of the system subject to the full bridge load should be calculated to determine the initial elevation for the temporary support setup. It is also recommended that a moving load analysis should be performed for the temporary support system considering forces developed in the direction of gravity, the slide, and the transverse of the slide.

- Usually, the design of bridge foundations do not consider the large horizontal forces induced by SIBC due to pull or push mechanisms. Hence, it is essential to evaluate the capacity of the substructure and foundation before the slide-in. The substructure should be evaluated for the effect of the uplifting force in the pier column and the overturning of the pier structure, the effect of the transverse forces (transverse to the sliding direction), especially for the unguided sliding system, etc.

- It was found that the difference between the applied force and resistance is not constant throughout the slide-in, which may result in binding and uncontrollable drifting. To allow accurate and rapid force control during the move operation, a servo controller is required. Laboratory tests associated with appropriate monitoring are one of the approaches that could be used to measure the difference between applied force and resistance to provide information for both bridge design and construction planning.

- Little field monitoring and analytical simulation has been conducted to investigate pier structure response during the slide-in, creating a large demand for research to fill this gap.

Although a significant amount of valuable information was collected from the literature search, it appears the performance of the substructure on multi-span bridges during the slide-in is still a new topic and that not a lot of research work has been conducted on it. The questions that could be answered through the survey that was done were relatively basic, and many questions were left unanswered, including questions surrounding the following topics:

- Drawbacks and advantages of pushing and pulling
- Drawbacks and advantages of two- and four-point pushing/pulling
- Efficiency of steering control during the slide to prevent binding with four support points
- Lateral flexural stress level of continuous girders at piers
- T-pier performance during the slide-in process, etc.

ANALYTICAL INVESTIGATION

Although the literature search was productive and provided a significant amount of valuable information, many questions were left unanswered. To address these questions, the researchers performed preliminary modeling. The objectives of conducting the analytical simulation were to investigate the structural behavior of the bridge piers during the bridge slide-in and evaluate the drawbacks and advantages of two- and four-point pushing.

The research plan with respect to the analytical simulation included two steps: 1) full-scale model and 2) parametric study. The modeling of the full-scale bridge provided insight regarding bridge behavior due to the lateral sliding load. The full-scale model was developed based on the onsite monitored bridge and was calibrated utilizing the field collected data. The parametric study investigated the effect of two- and four-point sliding on permanent bridge piers.

Model Development

The FE model was created based on the IA 1 Bridge over Old Man's Creek near Iowa City, Iowa, which was constructed utilizing the lateral slide method and instrumented for field monitoring (as shown in Figure 6).

Figure 6. IA 1 bridge orientation

The bridge has a length of 300 ft and a width of 47 ft-2 in., with three spans (90 ft, 120 ft, and 90 ft). The bridge superstructure consisted of seven rolled steel girders (W40x249) and an 8 in. reinforced concrete deck. The bridge permanent substructure consisted of two wall piers founded on 14 HP 16 x 101 driven piles each. The temporary pier consisted of six 1-ft diameter steel pipe piles capped with a steel beam. The two permanent piers were nearly identical in size and construction.

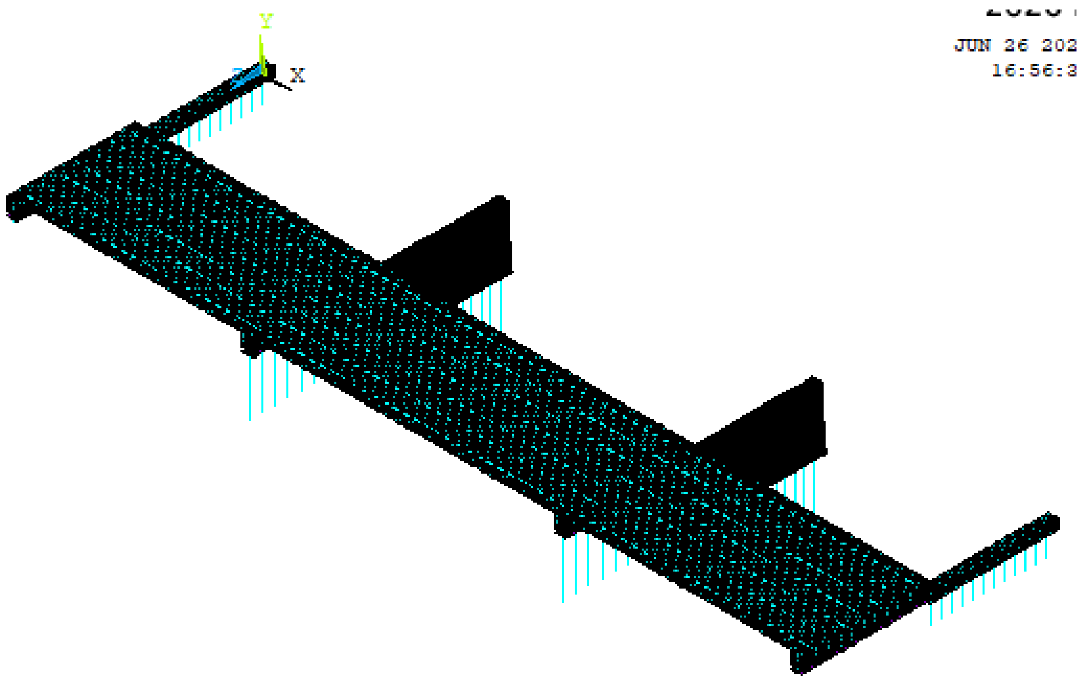
The traffic flow is in the north-south direction and the lateral slide was conducted from east to west. For a better identification of the orientation, a Cartesian coordinate system was established with y in the vertical direction, x in the bridge transverse direction, and z in the traffic direction. As shown in Figure 6, the permanent pier on the south was labeled Pier 1 and the other was labeled Pier 2. For additional information on the bridge details and sliding process, see the report from Liu et al. (2021).

To simulate a complete bridge slide-in process, the full-scale bridge model was created including both the temporary and permeant structures. Table 2 lists the bridge components and the detailed information used for the FE model.

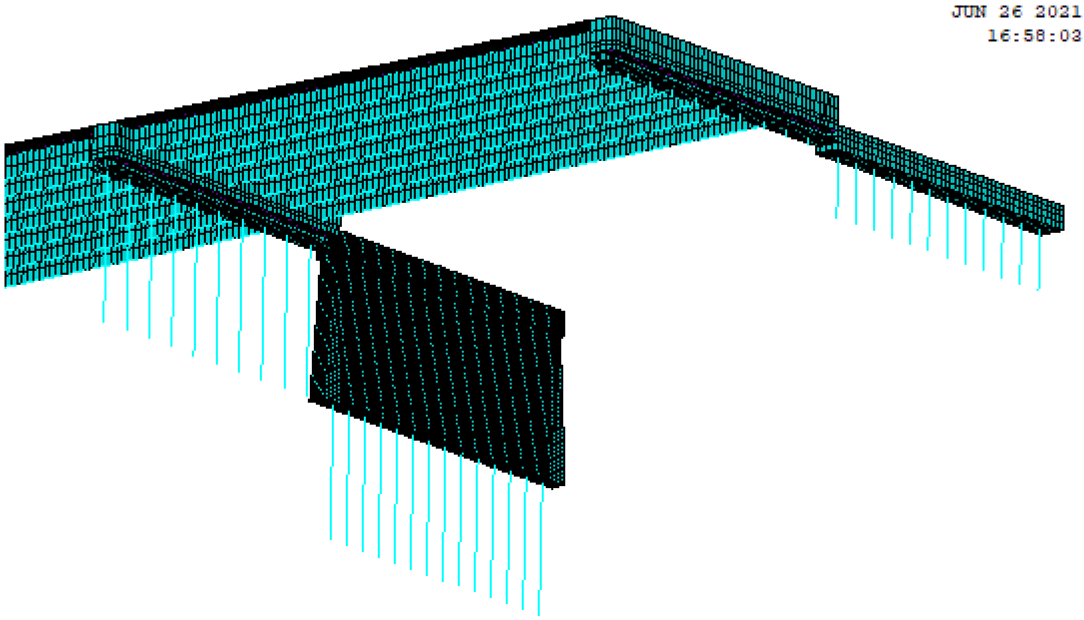
Table 2. Materials assignment

Component	Material type	Element type	Material properties			
			f'c **(ksi)**	**Young's modulus (ksi)**	**Density (lb/ft^3)**	**Poisson's ratio**
Abutment and pier piles	Steel	Shell and beam	–	29,000	500	0.3
Girders	Steel	Shell and beam	–	29,000	500	0.3
Temporary pier	Steel	Shell and beam	–	29,000	500	0.3
Temporary abutment	Concrete	Solid	4	3,865	150	0.18
Abutment and pier cap	Concrete	Solid	4	3,865	150	0.18
Pier wall	Concrete	Solid	4	3,865	150	0.18
Abutment and pier diaphragm	Concrete	Solid	4	3,865	150	0.18
Deck	HPC	Shell	10	5,760	150	0.18

The model included the bridge deck, rolled steel girders, abutment diaphragms and caps, pier diaphragms and caps, and embedded piles in the pier wall. Figure 7 shows a general overview of the model.



a) Model top view



b) Model bottom view

Figure 7. FE model

Multiple types of elements, including solid elements, beam elements, and shell elements, were utilized to establish the model as detailed in Table 2. For example, all of the concrete components on the substructure were modeled utilizing the three-dimensional (3D) solid elements. For the steel piles and rolled steel girders, the top and bottom flanges were modeled using beam elements, and the web was modeled using shell elements. Table 3 shows the dimensions of the piles and girders.

Table 3. Dimensions of piles and girders

Bridge component	HP10x57 (abutment)	HP16x101 (pier)	W40x249 (girder)	Element type in the FE model
Flange length (in.)	10.2	15.8	15.8	Beam
Web length + (2xflange thickness) (in.)	10	15.5	39.4	Shell
Web and flange thickness (in.)	0.565	0.625	1.42	Beam

The concrete deck was modeled utilizing the shell element. The temporary pier consisted of seven 20 in. diameter hollow circular steel columns and a rolled steel girder. In the model, the hollow circular steel columns were modeled utilizing the beam element and the steel girder was modeled in the same way that was used on the steel piles.

Given that no damage or cracking was observed during the slide-in and all of the collected data indicated that the bridge material was in the elastic region, the FE model was created with only elastic material properties. The previous Table 2 presents the material properties that were assigned to each component of the bridge model.

Based on the design plans for the bridge, the specified compressive strength (f_c') for the deck girder was 10 ksi and, for the concrete in the other bridge components, 4 ksi. The Young's Modulus for concrete was calculated by $57000\sqrt{f_c'}$ (ACI 2012), yielding the Young's Modulus of 5,760 ksi for the pre-stressed girder and 3,865 ksi for the other concrete components. All of the steel components were given a Young's Modulus of 29,000 ksi. Poisson's ratio for all of the concrete members was taken as 0.18 and, for the steel, it was taken as 0.3.

The steel reinforcement in the concrete deck was also taken into account by smearing them into the concrete in the model. To simulate this orthotropic behavior of the bridge, an effective thermal expansion coefficient (α_{eff}) and an effective Young's Modulus (E_{eff}) were determined using Equation 1 and 2 (Liu et al. 2016).

$$\boldsymbol{E_{eff} = \frac{A_c E_c + A_s E_s}{A_c + A_s}} \tag{1}$$

$$\boldsymbol{\alpha_{eff} = \frac{A_c E_c \alpha_c + A_s E_s \alpha_s}{A_c E_c + A_s E_s}} \tag{2}$$

where, E_{eff} is the effective linear elastic modulus of combined steel and concrete, α_{eff} is the effective thermal expansion coefficient of combined steel and concrete, $A_c$is the area of concrete, A_s is the area of steel, E_c is the linear elastic modulus of concrete, E_s is the linear elastic modulus of steel, α_c is the thermal expansion coefficient of concrete, and α_s is the thermal expansion coefficient of steel.

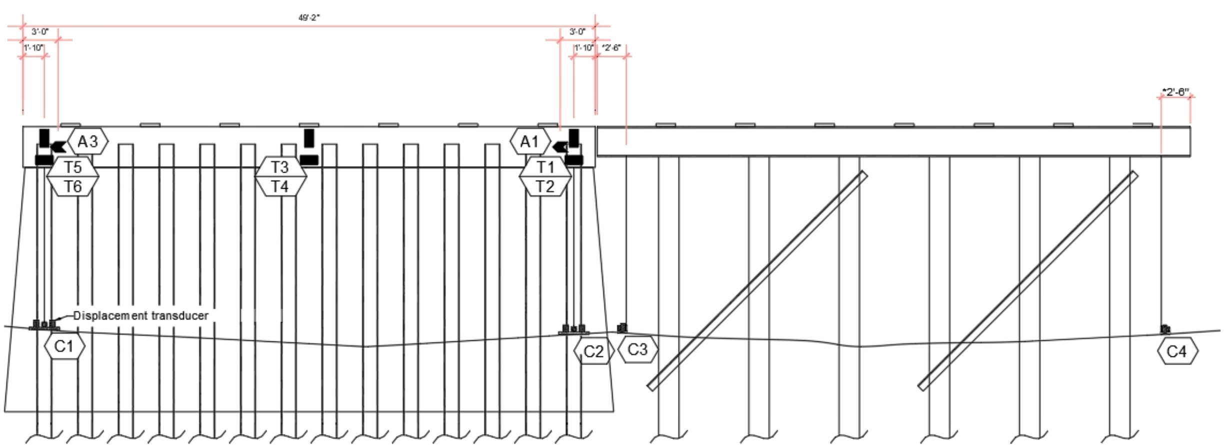
On the field monitored bridge, a fixed connection between the temporary and permanent piers was achieved by fastening the steel pile cap of the temporary pier into the face of the concrete permanent pier cap. A continuous steel channel was used across the temporary and permanent piers to guide the slide-in. Hillman Rollers were used, equipped with horizontal guide rollers that allowed them to use the guide channel and to be guided and maintained on the slide-in path. Eight sliding shoes were used at each pier, with each placed between the two adjacent girders under the concrete diaphragm. During the field slide-in, the bridge superstructure was pushed by four hydraulic jacks with one at each pier or abutment location.

On the FE model, the interaction between the bottom of the superstructure and the top of the substructure was modeled utilizing the surface contact element, which allowed for transfer of normal and frictional forces. A friction coefficient of 0.2 was assigned to the contact element. A fixed boundary condition was given at the bottom of each pile, and the length support was provided through the length of each pile. Although 95-ft long piles were utilized on the bridge, the effective length of the piles underneath the piers and abutments were calibrated on the model and eventually determined to be 38 ft.

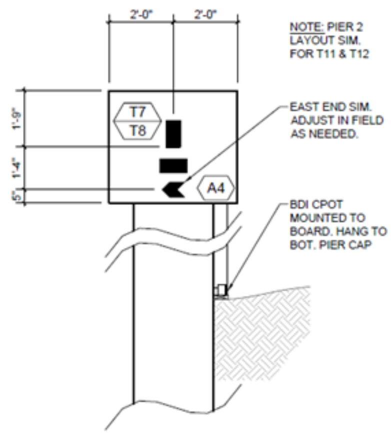
Model Validation

The field collected data were used to validate the FE model. Since the analytical study focused on the behavior of the bridge substructure, the field data collected from the bridge substructure were utilized (see the detailed field instrumentation work and full field data in Liu et al. [2021]). The model was validated by the estimated slide-in forces, pier vertical displacement data, and pier tilt data.

Figure 8 shows the instrumentation plan for the strain and displacement gauges on the pier.



a) Pier front face



b) Pier side view

Figure 8. Pier 1 instrumentation

During bridge monitoring, 12 tilt meters (T1 through T12) were utilized with eight on Pier 1 and four on Pier 2. As shown in Figure 8, for the instrumentation of Pier 1, T1 through T6 were installed on the south face of the pier cap, and T7 and T8 were installed on the side. Pier 2 was instrumented only at the middle of the pier front face and the side of the pier cap with T9 and T10 replacing T3 and T4 and T11 and T12 replacing T7 and T8. Among these tilt meters, T1, T3, T5, T8, T9, and T12 measured the rotation about the x direction, and T2, T4, T6, T7, T10, and T11 measured the rotation in the z direction. These tilt meters were used to monitor the pier caps for rotation.

In addition to the tilt meters, four displacement transducers (C1 through C4) were used to measure the movement in the vertical direction, with C1 and C2 installed on the permanent pier and C3 and C4 installed on the temporary structure (as shown in Figure 8).

Model Validation by Sliding Force

Although the forces that were used to slide the superstructure were not measured during the field monitoring work, these could be calculated by the estimated superstructure weight and the coefficient of friction. The superstructure consisted of the deck, steel girders, and pier and abutment diaphragms. The weight of the superstructure was calculated with a concrete density of 150 lb/ft^3 and steel girder weight from the American Institute of Steel Construction (AISC) steel code.

Table 4 shows the model validation results by the slide-in forces.

Table 4. Model validation by slide-in forces

Slide-in	Superstructure weight	South abutment	Pier 1	Pier 2	North abutment	Coefficient of friction	Summation
Forces (kips)	2,200	32	89	89	32	0.11	242

The total weight of the superstructure was about 2,200 lb. With a coefficient of friction of 0.11, the estimated total slide-in force was about 242 kips, which shows agreement with the summation of the slide-in forces from each diaphragm on the FE model.

Model Validation by Pier Vertical Displacement Data

The field test results indicated that the data from the C2 displacement transducer (at the side near the temporary structure) initially showed negative values after the superstructure moved onto the permanent piers, and, as the sliding continued, an uplifting action was observed. Comparing the data from the C1 and C2 displacement transducers, an opposite trend was observed during the second half of the slide-in. At the end of the slide-in, the data from C2 was about 0.04 in. greater than the data from C1. The analytical results showed similar results. Table 5 compares the displacement difference between C1 and C2 for the field test and analytical solution.

Table 5. Model validation by displacement difference between C1 and C2 from Pier 1

Difference	Field	FEM
Displacement (in.)	0.04	0.04

Model Validation by Pier Tilt Data

The model was further validated using the tilt data in the bridge transverse (x) and longitudinal (z) directions. Table 6 shows the model validation results by residual tilt data about the x and z directions on Pier 1.

Table 6. Model validation by tilt about the x direction on Pier 1

Residual tilt	T1	T3	T5	T8	FEM
x direction (degrees)	-0.03	-0.03	-0.03	-0.02	-0.02
z direction (degrees)	0.007	0.003	0.005	0.004	0.005

The results indicated that the field-collected residual rotation about the x direction from T1, T3, T5, and T8 ranged from -0.02 to -0.03, while the analytical solution gave nearly identical results of -0.02 for these instrumented locations. The residual rotation in the z direction from T2, T4, T6, and T7 ranged from 0.003 to 0.007, while the FE model gave similar results of 0.005.

Summary of the Model Validation Results

Given the objective of the analytical work focused on the bridge substructure, and specifically Pier 1 with the maximum response, only the field data collected from Pier 1 were used for the model validation. The results indicated that the field collected data and analytical results showed good agreement, the model can be considered a valid representation of the field monitored structure, and, hence, was it used for the analytical study.

Parametric Study

The objective of the parametric study was to investigate the effect of two- and four-point pushing/pulling on the permanent bridge piers. To achieve this objective, the two external loadings on the abutments were removed and only the two pier diaphragms were loaded to provide the lateral slide-in force.

Table 7 lists the critical results from the two-point loaded model.

Table 7. Parametric study results

FE Model	Sliding force on Pier 1 (or Pier 2)	Vertical displacement difference between C1 and C2 (Pier 1)	Residual tilt about x direction (Pier 1)	Residual tilt about z direction (Pier 1)
Two-point loaded	121	0.04	-0.022	0.053
Four-point loaded	89	0.041	-0.02	0.005

Comparing the results from Table 7 and the results from the field collected data and analytical results from the four-point loaded structure, the researchers found that, with two-point loading, the pier experienced a greater response. The difference in response between the two- and four-point loading scenarios was calculated utilizing the FE model results. In general, the two-point pushing manner increased the loading on the pier diaphragm by about 36%. Because of that, the pier response with respect to rotation about the x and z directions increased; however, this increase was not significant.

This phase of research included only preliminary modeling efforts as presented here, while future work is needed to address other variables of interest.

SUMMARY AND RECOMMENDATIONS FOR PHASE II

A comprehensive literature search was conducted to find relevant information on the implementation of SIBC on multi-span bridges. However, limited public information was found that directly related to the substructure behavior subject to the lateral slide load.

An analytical simulation was conducted to investigate the structural behavior of bridge piers during the bridge slide-in and to evaluate the drawbacks and advantages of two- and four-point pushing. To achieve this, an FE model was developed and validated against the data collected from a field monitored bridge.

The results indicated that two-point pushing increased the loading on the pier diaphragms by 36%. Because of this, the pier response with respect to the tilt about the x and z directions increased; however, this increase was not significant. By analyzing the field and analytical solution results, the researchers also found that the bridge pier experienced a greater rotation about the bridge transverse direction than about the longitudinal direction.

Detailed Recommendations for Future Work

Based on the findings presented in this report, the following areas of interest for future work were identified:

- Drawbacks and advantages of pushing and pulling
- Lateral flexural stress levels of continuous girders at the piers
- Performance of different types of piers (including T-piers, beam-column frames, etc.) during the slide-in process
- Effect of the uplifting force in the pier column and in overturning of the pier structure
- Behavior of steel and concrete diaphragms
- Efficiency of steering control during the slide to prevent binding with four support points
- In-depth study of lap-splice strength development for closure pour applications

To best address the above topics, laboratory testing in conjunction with further FE modeling is suggested. These efforts are further described below.

Laboratory Evaluation

The objective of the laboratory evaluation is to investigate the effect of the slide-in process on the substructure and provide the data for the calibration of the FE model to be developed in the subsequent task. In addition, the results from the laboratory study are expected to directly answer many of the questions surrounding the topics.

The slide-in process will be evaluated on a scaled specimen in the laboratory. Prior to the laboratory tests, a long and narrow bridge about 300 ft long with three spans will be selected and scaled down to 1/4 to 1/5 of its original size. Based on conversations with the bridge engineers at the Iowa DOT, one of the concerns from the design engineers is the flexural stress level of continuous steel girders during the slide of the superstructure. A long and narrow bridge with a relatively low superstructure stiffness would result in great flexural stress during the slide-in.

The test specimen will consist of all bridge components above the ground, including the bridge deck, girders, abutment, diaphragms, and temporary and as-designed pier frames. Additional Phase I work is to include field tests on a steel plate girder bridge, so the test specimen will keep consistent with the Phase I work and use steel girders.

Given the goal of this work is to focus on the pier region, a stub-abutment will be assumed and simplified to a large concrete block that is sufficient to provide enough support to the superstructure at the ends in the laboratory without any additional restrictions for the workspace. Two pier types will be constructed and tested: the T-shaped pier and the column-beam frame. One pier will be constructed for each type, and both will be placed under the superstructure and simultaneously tested.

Table 8 presents the proposed Phase II laboratory test matrix.

Table 8. Phase II laboratory test matrix

Test no.	Girder	Abutment	Abutment diaphragms	Diaphragms over piers	Pier type	Actuating system	# of load application locations	Sliding system
1	Steel	Concrete	Concrete	Steel bracing	T Pier and Beam-Column Frame	Hydraulic Jack	2	Roller
2					T Pier and Beam-Column Frame	Hydraulic Jack	4	Roller
3	Steel	Concrete	Concrete	Concrete	T Pier and Beam-Column Frame	Hydraulic Jack	2	Roller
4					T Pier and Beam-Column Frame	Hydraulic Jack	4	Roller
5					T Pier and Beam-Column Frame	Post-tensioning	2	Roller
6					T Pier and Beam-Column Frame	Post-tensioning	4	Roller
7					T Pier and Beam-Column Frame	Post-tensioning	2	Teflon
8					T Pier and Beam-Column Frame	Post-tensioning	4	Teflon

Eight tests will be conducted and each test will be performed twice to collect reliable data. During the tests, the steel girder, concrete deck, stub-abutment, concrete abutment diaphragm, and one T-shaped pier plus one beam-column frame pier will be used and kept the same in each test. The specimen will first be constructed with steel bracing for the pier diaphragm and pulled with hydraulic jacks and roller supports. After that, the steel bracing will be removed and a concrete diaphragm will be constructed over each pier. The superstructure will be tested using a hydraulic jack and roller system, post-tensioning force with a roller system, and post-tensioning force with Teflon pads. As shown in Table 8, each combination will be tested with two loading points and four loading points, respectively.

During the laboratory evaluation, the whole superstructure will be moved from the temporary pier frame to the as-designed pier frame. The structural behavior at the critical locations such as deck top, pier diagram, and pier cap and columns, will be monitored using strain gauges and displacement transducers. A detailed instrumentation plan will be carried out to monitor the structural responses as follows:

- Overall lateral slide force effects on the piers
- Overturning effects on the piers
- Uplift effects and forces caused on the piers
- Friction forces and effects at the bridge's transition from the temporary supports to the final substructure

Finite Element Analysis/Simulation

The objective of the analytical simulation is to investigate the structural behavior during the superstructure slide-in process. The analytical simulation will be conducted utilizing the FE method. The results from the FE model analysis will provide the researchers with insights into the stress levels on the whole structure (where instrumentation might not have been installed on the laboratory test specimen or on the bridge being monitored during Phase I in the field). To obtain a validated model and solid analytical results, the simulation work will be conducted in three steps: scaled model, full bridge model, and parametric study.

In **Step 1**, the model will be developed based on the scaled laboratory test specimen. The data collected during the laboratory tests will be used to calibrate the model. The goal of this step is to understand the structural behavior during the slide-in with different structural element and equipment type combinations, as listed in Table 8, are used. The performance of this step will help the researchers to obtain a valid modeling approach for each individual combination in Table 8. These modeling approaches will be used in the subsequent steps.

In **Step 2**, a full bridge model will be created based on the bridge tested during the Phase I work. The data collected during the field test in Phase I will be used to calibrate the model and validate the modeling approach on a full-scale basis.

In **Step 3**, a parametric study will be performed on a full-scale basis. The model developed in this step will utilize the modeling approaches validated in Step 1 and 2. Given that the laboratory tests and simulation work conducted in Step 1 were on a small-scale basis and the field test with modeling work in Step 2 were performed with only one structural element and equipment combination, the performance of the other combinations on a full-scale basis remains unknown. The objective of this step will be to investigate the performance of the other combinations. The results can then be used to develop recommendations for design and construction.

Since the model will be developed to simulate the new bridge superstructure slide-in during construction, the material properties for each bridge component will be defined in the elastic range assuming no plastic deformation or damage occurred during the slide-in. However, a nonlinear analysis with large steel deformation needs to be performed to simulate the relative movement and contact behavior between the superstructure and the substructure. The strain and displacement results at the instrumented locations will be output and compared with the test data for the models in Step 1 and 2. The stress levels in each model at the non-instrumented locations will be further investigated on the validated model.

REFERENCES

Aktan, H. and U. Attanayake. 2015. *Research on Evaluation and Standardization of Accelerated Bridge Construction Techniques: Part I and Part II*. Western Michigan University, Kalamazoo, MI.

Hwang, J. S., K. C. Chang, and G. C. Lee. 1990. Quasi-Static and Dynamic Sliding Characteristics of Teflon-Stainless Steel Interfaces. *Journal of Structural Engineering*, Vol. 16, No. 10, pp. 2747–2762.

IDOT. 2011. *Bridge Condition Report: Procedures & Practices*. Illinois Department of Transportation, Bureau of Bridges and Structures, Division of Highways, Springfield, IL.

Liu, Z., K. S. Freeseman, J. M. Dahlberg, B. M. Phares, and M. LaViolette. 2021. *Lateral Slide of Multi-Span Bridges: Investigation of Connections and Other Details–Phase I*. Bridge Engineering Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2021/06/multi-span_lateral_slide_connections_investigation_phase_I_w_cvr.pdf

Phares, B., S. Mousavi, and Y. "J." Deng. 2019. *Construction of New Substructures Beneath Existing Bridges*. Bridge Engineering Center, Iowa State University, Ames, IA. https://intrans.iastate.edu/app/uploads/2019/05/new_substructures_beneath_existing_bridges_w_cvr.pdf.

Ridvanoglu, O. U. 2016. Developing Standard Procedures for Structural Aspects of Slide-In Bridges in Accelerated Bridge Construction (ABC). MS thesis. Western Michigan University, Kalamazoo, MI.

Ridvanoglu, O., U. Attanayake, and H. Aktan. 2017. Monitoring during Lateral Bridge Slide. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2630, pp. 23–32.

Shutt, C. A. 2013a. Accelerated Bridge Construction: Sliding and Rolling Bridge Solutions – Part 1. *ASPIRE: The Concrete Bridge Magazine*, Winter, pp. 21–23.

Shutt, C. A. 2013b. Accelerated Bridge Construction: Sliding and Rolling Bridge Solutions – Part 2. *ASPIRE: The Concrete Bridge Magazine*, Spring, pp. 19–20.

Shutt, C. A. 2013c. Accelerated Bridge Construction: SPMT Solutions. *ASPIRE: The Concrete Bridge Magazine*, Fall, pp. 39–41.

UDOT and Michael Baker Corporation. 2013. *Slide-In Bridge Construction Implementation Guide: Planning and Executing Projects with Lateral Slide Method*. Federal Highway Administration, Washington, DC.

Zekkos, A. A., R. D. Woods, and A. Grizi. 2013. *Effect of Pile-Driving Induced Vibrations on Nearby Structures and Other Assets*. University of Michigan, Ann Arbor, MI.