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Developing Standard Procedures for Structural Aspects of Slide-in Bridges in Accelerated Bridge Construction (ABC)

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DEVELOPING STANDARD PROCEDURES FOR STRUCTURAL ASPECTS OF SLIDE-IN BRIDGES IN ACCELERATED BRIDGE CONSTRUCTION (ABC)

by

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Slide-in bridge construction (SIBC) is a special method especially used to replace an existing bridge with the minimum duration road closure. In this method, new bridge superstructure is built next to the existing one and it is slid to its final position after demolishing the existing one. Applied implementations of SIBC show that several complications are experienced during bridge slide related with surface interaction. There is a need to evaluate the structural components of SIBC to develop suggestions. In this research, structural components of SIBC were investigated. The research dealt with completed SIBC implementations and numerical modelling of the slide process with performed simulations to understand the fundamental parameters that influence the slide process. Potential difficulties which may occur during the slide are identified as an outcome of simulations as a result of an understanding fundamentals of sliding process. The results of the research is intended for developing standard procedures that overcomes the difficulties observed in implemented projects.

Dedicated to my parents, Nimet and Suleyman Ridvanoglu.

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Ozan Utku Ridvanoglu

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CHAPTER I

INTRODUCTION

An existing bridge replacement is an engineering problem, which needs to be analyzed considering the mobility impacts long closure can bring. Absence of the connection between each side of the bridge brings several difficulties to the people using that road and inconveniences to businesses near the bridge. Detours may generate a large amount of delay in safety and emergency situations, which may create difficulties for travelling public. Detours may also result in traffic congestion resulting in increased fuel consumption, along with air and noise pollution. On the other hand, businesses are directly affected by the bridge closure resulting in negative effects to the local economy. Different construction techniques are introduced in the literature in order to prevent the potential negative consequences stated above. Accelerated Bridge Construction (ABC) is a bridge construction method that includes innovative planning, design and materials in order to reduce onsite construction time while considering safety and cost efficiency, according to FHWA (2011). The goal of the ABC is to minimize road closures and traffic disruptions, SHRP 2 R04 (2013).

Several ABC methods used worldwide are listed in Aktan and Attanayake (2013). Among those listed, Self-Propelled Modular Transport (SPMT) and Slide-In Bridge Construction (SIBC) are the two popular methods. These methods are shown in Figure 1a, b. In this research SIBC methods are discussed.

(a) SPMT move
(Sam White Lane Bridge, Salt Lake City, Utah)

(b) SIBC
(M-100 Bridge, Potterville, Michigan)

Figure 1. ABC examples

Background

Slide in bridge construction (SIBC) is an Accelerated Bridge Construction (ABC) Method. SIBC requires construction of a new superstructure near an existing bridge. A new superstructure is slid into permanent position following the removal of the existing bridge. In this method, an old substructure can be retained or a new substructure can be built. SIBC prevents long road closures which minimizes adverse mobility effects on users. Traffic is maintained on the existing bridge during the construction of new superstructure. After completion of the new superstructure, traffic is shifted and maintained on the new superstructure. A new superstructure is slid into final alignment by a procedure called lateral bridge slide. There is a minimum duration road closure during lateral bridge slide. This duration is dependent on the project, and this project uses the ABC method. Five tiers are defined for implementation duration for ABC projects in SHRP 2 R04 (2013). Lateral bridge sliding is classified as Tier 1, which includes bridge replacement within 1 to 24 hours of mobility impact.

SIBC requires additional activities when compared to conventional bridge construction to perform a lateral bridge slide. These activities are constructing temporary structure to support the superstructure before sliding, sliding systems including rails, sliding shoes, Polytetrafluoroethylene (PTFE) pads or rollers, and actuating systems such as hydraulic jacks and pumps to initiate and maintain the sliding. These components are described throughout this document.

(a) Temporary sliding support structure

(b) Actuating system (c) Sliding system

Figure 2. SIBC components

The sequence of SIBC stages are listed as follows:

1^{st} → Construction of temporary sliding support structure
2^{nd} → Construction of superstructure on temporary structure
3^{rd} → Removal of existing superstructure or superstructure and substructure
4^{th} → Construction of new substructure
5^{th} → Lateral slide of the superstructure from temporary sliding support to new substructure and placing on permanent bearings.

Construction stages of one of the completed SIBC project in Potterville, Michigan, M-100 Bridge over CN Railroad are shown in Figure 3.

(a) 1^{st} stage

(b) 2^{nd} stage

(a) 3^{rd} stage

(a) 4^{th} stage

(a) 5^{th} stage

Figure 3. SIBC construction stages (Source: MDOT website)

The slide method has many applications in other industries. The new safe Chernobyl confinement is one of the biggest scale sliding projects ever designed. A 35000 T arch shaped confinement structure was designed to be slid 350m in order to close the Chernobyl reactor from spreading nuclear waste (Mammoet, 2015). A special skid system was designed; which included 116 skid shoes equipped with hydraulic jacks and Teflon Pads to slide this large structure. A servo controller system only allowed around 1 in. alignment tolerance in the transverse direction. This project uses the same methodology in SIBC. It is possible to use this technique in much heavier structures also. The areal figure and skid system are shown in Figure 4.

(a) Areal view (b) Skid system

Figure 4. Chernobyl Confinement (Source: Mammoet website)

Many benefits of SIBC are described in UDOT (2013). Safety concerns are greatly decreased in SIBC since the vehicular traffic and construction site are separated. SIBC also reduces on site construction time compared to conventional construction. In addition, mobility effects are significantly reduced in SIBC applications. Although additional components, such as a temporary structure and sliding systems, introduce additional cost, SIBC decreases the total cost because of the savings of user costs. Constructability and final product quality are also increased as additional benefits. On the other hand, limited right of way for staging, geometric constraints, lack of or limited SIBC experience, profile changes and utility impacts are listed as limitations of SIBC. These limitations are evaluated, and standard procedures are proposed to overcome the complications and challenges observed in the SIBC method throughout this document.

Objective and goals

The objective of this research is to develop and propose standard procedures for lateral bridge operation of SIBC. The objective is achieved by analyzing completed SIBC activities throughout the US and developing finite element (FE) models to simulate and demonstrate the reasons and the effects of challenges observed during sliding. Standard procedures for a lateral slide design and operation of SIBC are developed from the evaluation of case studies and simulation outcomes. The goal is to develop system selection and design consideration charts, which can help to guide the design of SIBC components. According to the results stemming from analyses of previous implementations and FE simulations, standard procedures are developed as recommendations to future SIBC implementations.

Methodology

Methodology includes collecting and analyzing information from implemented SIBC projects and literature with FE simulations outcomes. The following tasks are completed through the study:

- Documentation of SIBC processes and implementation challenges
  - Through literature collected from Federal Administration of Highways (FHWA) and State Department of Transportation databases.
  - Field Monitoring of SIBC projects in Michigan
  - Other literature (slide operation equipment manufacturers)
- Development of finite element (FE) simulation models of SIBC activities.
- Development of solutions to overcome the SIBC implementation difficulties towards standardization of the procedures.

Chapter 2 describes the components of SIBC implementations; Chapter 3 describes evaluation of methods and procedures used in completed SIBC implementations and FE simulations; Chapter 4 discusses standardization alternatives; Chapter 5 includes summary, conclusions and future research recommendations, Chapter 6 lists the references, and Chapter 7 explains used abbreviations throughout the document.

CHAPTER II

COMPONENTS OF SIBC IMPLEMENTATIONS

Overview

SIBC implementations require additional activities compared to conventional construction. SIBC implementation at a minimum requires a temporary structure, slide system and actuating system. Some applications may require additional components such as a vertical lifting system. These activities of SIBC are described in this section. Activities are later evaluated in Chapter 3 from completed, SIBC implementations in the US and by FE simulations.

Sliding Systems

Sliding systems provide and maintain a path to the superstructure during lateral slide. These systems may be guided and unguided. Polytetrafluoroethylene (PTFE) or Teflon pads and rollers are the most commonly used surfaces of slide systems in SIBC. Guided systems include restraints in the transverse direction to limit drift in the direction perpendicular to sliding. Rollers are commonly used in guided systems, but Teflon pads and rollers can be utilized in conjunction with the guides to provide smooth sliding with restraints to transverse movement. There are no transverse restraints in unguided systems. Thus sliding require cautious monitoring for transverse direction movements. There is no best system for any specific application (UDOT 2013). Geometry, weight, tolerances and experience are the parameters considered in the selection of slide systems. Rollers and Teflon pads are briefly explained in this section, and guided and unguided systems are described in Chapter 3.

Rollers

Rollers are placed under the girders or end diaphragms and inside sliding tracks to provide bridge movement during sliding. Rollers are restrained by sliding tracks in the transverse direction of sliding. As a result, movement in the transverse direction is restrained during sliding performed with rollers. Most of the time movements in the transverse direction are not desirable. However, a final adjustment in the transverse direction may be necessary at the end of sliding. Challenging situations may develop for final adjustments since

movement in the transverse direction is not possible with rollers. In addition, sliding friction is very low in roller systems. The coefficient of friction in the Massena Bridge Slide was between 2.5% and 5% according to Hawash and Nelson (2014). In addition, breakaway friction in rollers is stated to be less than 5% of the weight in Hillman (*n.d.)*. Kinetic friction can be assumed to be the same as breakaway friction since the velocity is slow enough. In a hardened steel sliding surface, which is the case in SIBC most of the time, friction is even lower in roller systems. As a result, hydraulic systems can be of lower capacity. Advantages and challenges of rollers are listed in UDOT (2013). Advantages are being simple, inexpensive and easily accessible. Drawbacks are large point loads under the rollers, along with demanding a clean and properly aligned sliding track in order to prevent binding or jamming. In addition, the hydraulic system must have pulling and pushing capabilities to hold the structure in case of binding or jamming of the rollers. More attention is required in permanent and temporary substructures due to large point loads applied by rollers and the necessity of vertical jacking for placement and removal of rollers (SHRP2 R04 2015). An example of a roller system is shown in Figure 5.

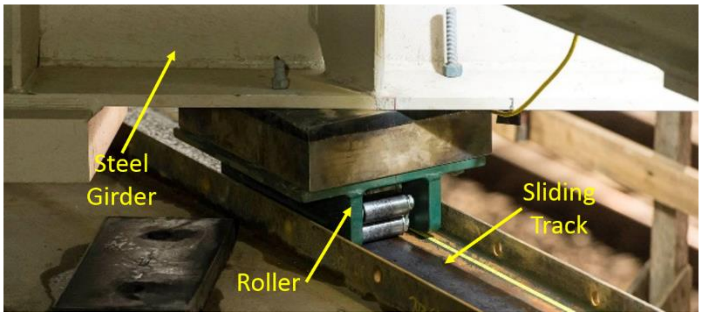


Figure 5. Roller (M-100 Bridge over CN Railroad, Michigan Source: MDOT webpage)

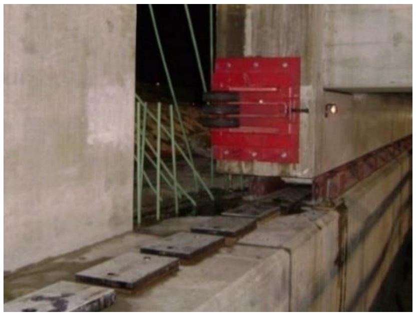
Polytetrafluoroethylene (PTFE) Pads (Teflon®)

Teflon pads are the most commonly used sliding system in lateral bridge slides. Teflon pads are used with sliding shoes. Sliding shoes can be designed for sliding and as a permanent bearing for bridges after sliding (SHRP2 R04 2015). Pads can be used with tracks or without tracks resulting with larger tolerances for transverse movements. Movement in a transverse direction is possible with pads, which can be a challenge to keep the superstructure in-line. Pads can be an advantage allowing the adjustment of the final superstructure position. Side rollers maybe used in order to keep the superstructure aligned. Sliding resistance is relatively large compared to rollers, but resistance can be

decreased with the use of lubricants. Several biodegradable lubricants, such as dish soap, are available. (Shutt 2013a). Static friction can be larger than kinetic friction in Teflon pads systems because of the pads are generally installed before construction.

Parameters that affect Teflon-steel interface friction are listed as 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 sliding direction (Hwang et al. 1990). In addition, AASHTO (2014) Table 14.7.25-1 shows that kinetic friction decreases with increase in normal pressure and use of lubrication. For example, Bondonet and Filiatrault (1997) conducted a series of experiments to evaluate the friction coefficient at the teflon-steel interface . The results show that static friction changes between 20% and 5% while kinetic friction changes 14% and 5% with different normal pressure and velocity combinations. Several studies completed on PTFE- steel interface with different normal pressure, velocity and surface roughness are combined, and the friction coefficient varies between 8% and 1% in Hwang et al. (1990). Friction coefficients for Teflon pads are also summarized from FHWA, DOT and manufacturer sources in Aktan and Attanayake (2015). Static friction varies from 5% to 15% while kinetic friction varies between 1% and 6%.

Advantages of the pad system are listed as being relatively inexpensive and allowing adjustments in transverse direction movements for final position in UDOT (2013). Disadvantages are listed as possibility of binding or jamming and damaging of pads and undesired transverse movement causing drifting of the superstructure. Examples of Teflon pad systems are shown in Figure 6.



(a) M-50 over I-96 Bridge sliding

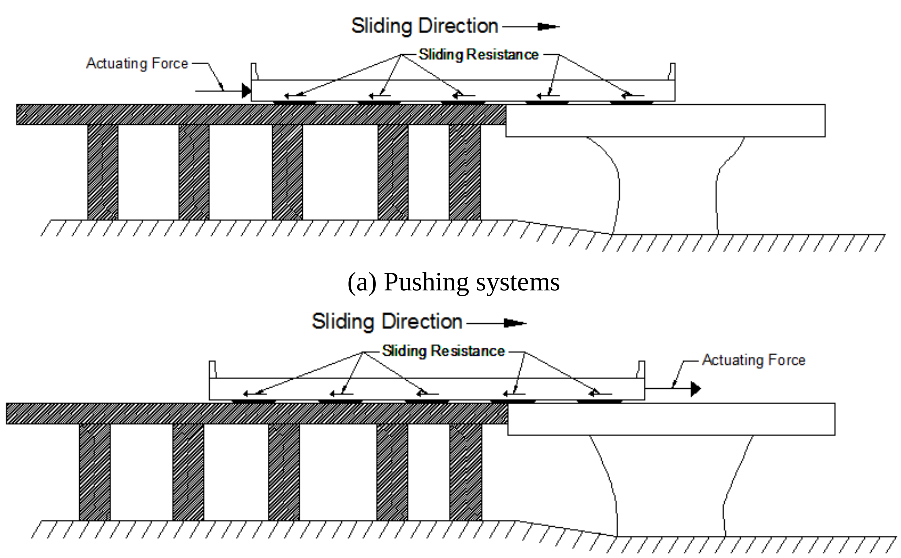
(b) US-131 over 3-Mile Road Bridge sliding

Figure 6. PTFE pads

Actuating Systems

Actuating systems provide force to initiate and maintain the sliding. Sliding can be completed by either pushing or pulling the substructure from the temporary position to permanent location. Hydraulic rams and prestressing jacks are the most commonly used devices for actuating the slide. Several factors affect the selecting the actuating systems such as terrain, bridge design and contractor's preferences as listed in FHWA (2014a).

Free body diagrams of pulling and pushing systems are shown in Figure 7. Force applied by the actuating system should be greater than the sliding resistance in order to initiate and maintain the sliding. The difference between the applied force and resistance is not constant throughout the sliding. Resistance can be estimated from experiments; however, will be changing due to its being dependent on several parameters. As a result, the difference between actuating and resistant forces inevitably varies between each abutment. This may result in binding on one side, with uncontrollable drifting of the superstructure. In order to prevent the drift, displacement should be monitored during sliding in both actuating systems. Uneven movements are frequent, and monitoring the displacement is essential for early corrections, which may prevent misalignments (Shutt 2013b).



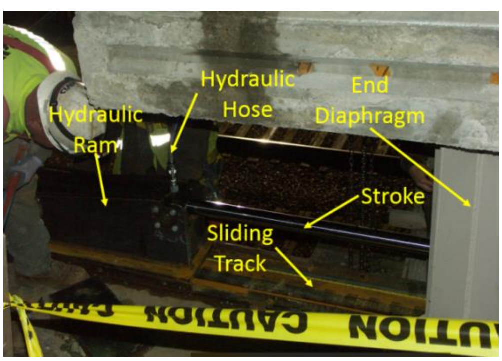
(a) Pushing systems

(b) Pulling Systems

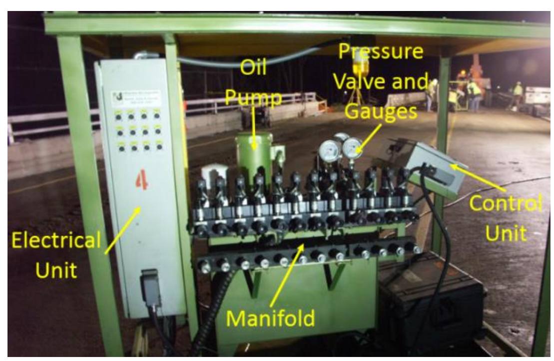
Figure 7. Actuating systems

Hydraulic Rams

Hydraulic Ram devices include hydraulic cylinders and power/operation control units. Generally, hydraulic cylinders are connected to superstructure diaphragms over the abutments and piers, and cylinders are capable of pulling and pushing. Cylinders are connected to a power/operation control unit with hydraulic lines or hoses. Oil pumps, a reservoir, pressure valves and gauges, a cylinder control manifold and a control panel are vital components that need to be included with rams to provide a smooth slide. An example system is shown in Figure 8. The capacities and properties of the components are project specific. However, capacity and stroke length of the hydraulic cylinders are important for the slide especially for preventing binding. Various stroke lengths and capacities are utilized in different projects, as described in Section 3. Stroke length between 6 and 18 in. is recommended while a stroke length longer than 30 in should be avoided (Shutt 2013a). Binding may result causing damage to the superstructure in the use of longer stroke length cylinders, if the binding occurs in the beginning of the pushing cycle and if the binding is not noticed. This event may be prevented by monitoring and/or using a short stroke length cylinder. Some designers suggest that the capacity of the cylinders should be selected equal to designed resistance to prevent excessive forces, which may develop in the case of binding Shutt (2013b). A servo controller can be utilized to monitor real-time displacement in different rails in order to control equal sliding rate. Aktan and Attanayake (2015) suggest that a servo controller system is a necessity to monitor displacement and/or force during the slide.



(a) Hydraulic cylinder and assemblies



(b) Power/operation control units

Figure 8. Hydraulic actuating system

Prestressing Jacks

Prestressing jacks include a high strength steel cable or rod attached to the superstructure generally at end diaphragm locations. These systems are generally used with a pulling operation since jacks can only apply tensile forces. However, pushing can be utilized with prestressing jacks in special designs. Jacks require a hydraulic pump and reaction frame. Example of prestressing jack is shown in Figure 9. A breaking system should be considered for emergency situations (SHRP 2 R04 2015). For example, a break cable was implemented in the lateral bridge slide of Northeast 8th Street Bridge in Washington (Rem and Kayle n.d.). Another prestressing jack can be utilized in the opposing side of the superstructure to develop push/pull systems. In addition, cable systems do not require settling for each pulling cycle. Jacks provide more continuous slide since resettling operations are simpler after each pull. However, cable flexibility and prestressing losses can generate jerk in movement (UDOT 2013).

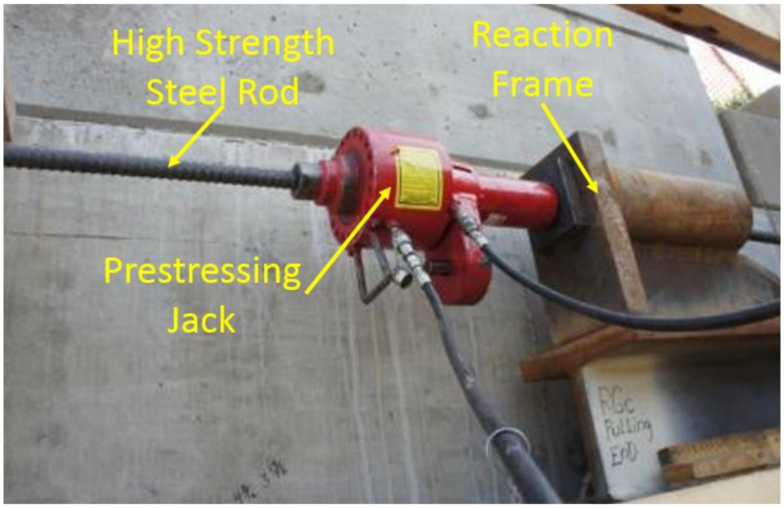


Figure 9. Prestressing jack (US 131 Bridge over 3 Mile Road)

Temporary Structure

The SIBC method requires a temporary support structure. It is built to support the superstructure loads during the construction before and during the lateral slide. Loads transferred to temporary supports by friction forces need to be taken into consideration as well as gravity loads such as weight, traffic, and equipment load in the design. Despite the fact that different materials can be used in temporary structures, steel is favorable due to its recycle value.

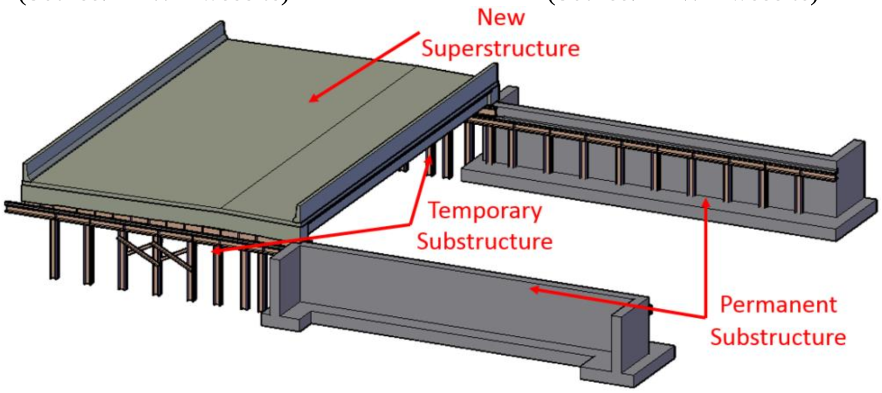
Temporary structures include a foundation, a frame system and a sliding track. Driven piles, drilled shafts, micro-piles or spread footing can be used as a foundation. The foundation of the permanent abutments or piers can also be used as a foundation of temporary supports in specific applications. Columns, piles, and bracing members are used in the frame system. A temporary structure includes a longitudinal railing girder. The sliding track is supported by a railing girder. Continuous support should be provided to the sliding track. Moreover, stiffness of permanent and temporary support structures affects the sliding resistance. The design of a temporary support system requires consideration of lateral forces generated by slide to prevent undesirable stress increases in a sliding superstructure due to expected deformations (SHRP2 R04 2015). Examples are shown in Figure 10a, b.

There are two types of orientation possible in support systems: inline and infront. Inline supports resist superstructure loads during construction and the initial stage of sliding. An inline support is connected to the permanent structure, and sliding is maintained from temporary supports to the permanent substructure. Design and construction of connection between the temporary and permanent substructure has significant importance to assure a smooth transition during the slide. Development of large point load is possible just before crossing from temporary support to permanent substructure, which can result in a deflection difference creating a slide obstacle (UDOT 2013). Infront temporary structures include construction of a temporary support system for the full sliding operation. Lateral slide is operated on a temporary structure, and transfer to the permanent substructure is performed after the slide to permanent alignment. These types of systems require vertical lifting after the slide in order to place the superstructure on permanent location. A

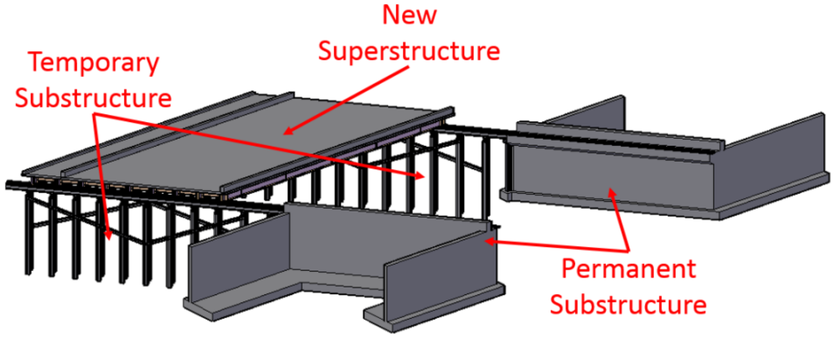
permanent foundation can be used for the portion of the temporary supports, which is aligned with the permanent substructure. Inline and infront temporary supports are shown in Figure 10c, d.

(a) Bridge on I-75 over U.S. 6
(Source: FHWA website)

(b) Crossing 3 over Elkcreek
(Source: FHWA website)



(c) Infront structure



(d) Inline structure

Figure 10. Temporary structure types

Summary

Components of SIBC implementations are listed as sliding system, actuating system and temporary structure. Rollers and Teflon Pads are identified as typical applications of sliding system. Hydraulic rams and prestressing jacks are identified as typical applications of actuating system. Inline and infront types are identified as typical applications of temporary structure. Characteristics of each component are explained. Further, evaluation of methods and procedures of SIBC standardization chapter investigates each component through implementations and simulations.

CHAPTER III

EVALUATION OF METHODS AND PROCEDURES FOR SIBC STANDARTIZATION

Overview

Nationwide SIBC projects are studied to analyze the systems utilized and evaluate advantages and challenges recorded for each implementation. A classification of sliding systems, actuating systems and temporary structure is developed from the findings. Standardization alternatives and design considerations are developed for lateral slide systems. In addition, finite element models are developed to simulate and corroborate the findings. In this chapter evaluation of findings from implementation projects and finite element simulations are explained.

Methodology for data collection and modelling

A literature review was performed to collect data from implemented SIBC activities. The Federal Highway Administration (FHWA) and Departments of Transportation (DOTs) databases were scanned for this purpose. In addition, three SIBC projects completed in Michigan were monitored and findings are documented. Journal articles and conference proceedings describing SIBC activities and SIBC equipment manufacturers' publications are also included.

In addition to monitoring field implementations, finite element models are developed. Utilization of different type of components for the systems are evaluated with simulations. Simulations are also used to verify the source and management of challenges.

SIBC Implementations

Typical SIBC components utilized are described in Chapter 2. As a first stage, 28 completed SIBC implementations are evaluated for the sliding system, actuating system and temporary sliding support structure. Different components of each system's pros/cons and design considerations are listed. Later evaluation results are used to develop standard procedures.

Name, location, girder type and total span number & length of each project are listed in Table 1, Table 2 and Table 3. Although the concrete bulb tee and steel I girder bridges are the most

common, a variety of other girder types can be utilized with SIBC. SIBC is mostly preferred in single span bridges. However, there are completed bridge slides of up to six spans. Total span length of the majority of bridges is between 100 and 150 ft, yet there are a significant number replaced with SIBC with a total length greater than 300 ft.

Outcome of this investigation will be mostly valid for single or two span bridges with a total length up to 200 ft. When span numbers and length increase, additional design factors should be taken into consideration, which is outside the scope of this study. Distribution of girder type, span numbers and total length of the 28 SIBC projects are shown in Figure 11, Figure 12, and Figure 13 respectively.

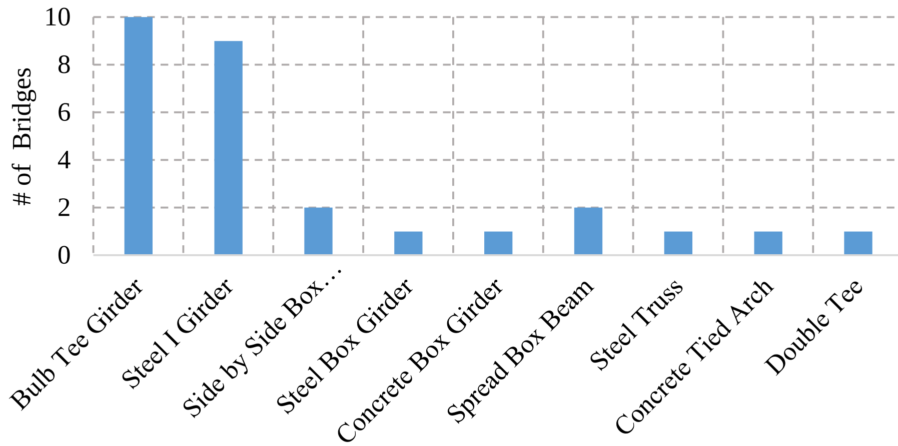


Figure 11. Different girder types in completed SIBC implementations

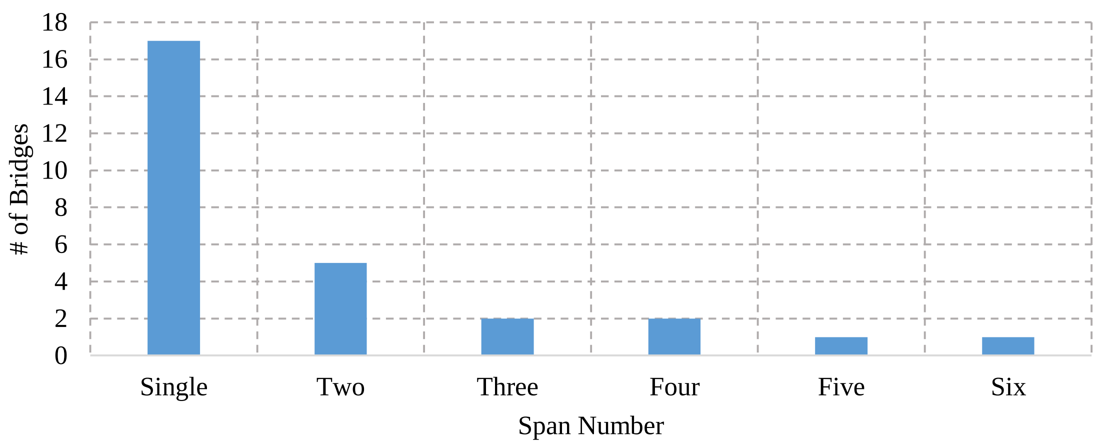


Figure 12. Spans of completed SIBC implementations

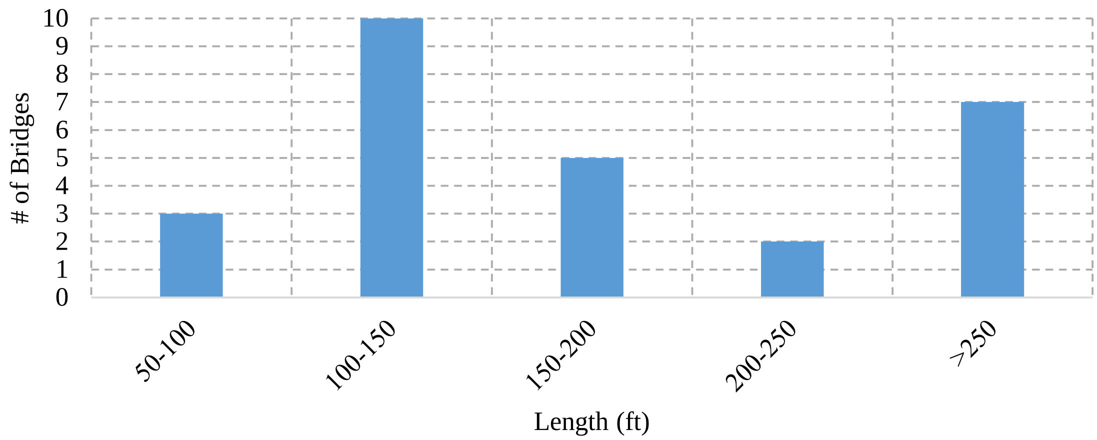


Figure 13. Different total span length in completed SIBC implementations

Sliding Systems

Sliding systems are classified according to tolerances in transverse direction movements, type and method of sliding surfaces. Transverse movements are controlled and limited in guided systems while there is no restraint in unguided systems, which allows the superstructure to move in a transverse direction. Teflon pads, rollers or steel plates can be used as a sliding surface. Bridge slide can be performed with temporary bearings, or permanent bearings. A classification approach for sliding systems is shown in Figure 14.

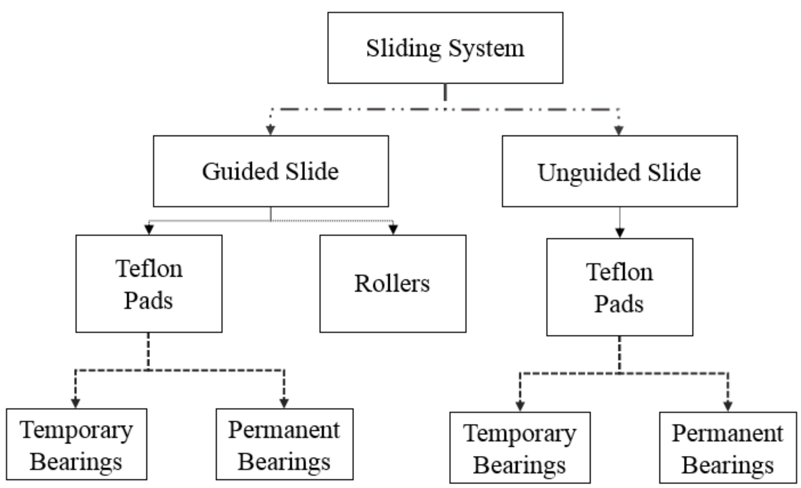


Figure 14. Classification approach for sliding system.

Classifications of slide system components used in completed implementations are summarized in Table 1. Name, location, number of spans, total span length, and girder type of each project are listed. The type of transverse restraint system used, along with the sliding surface and sliding bearing for each project are identified.

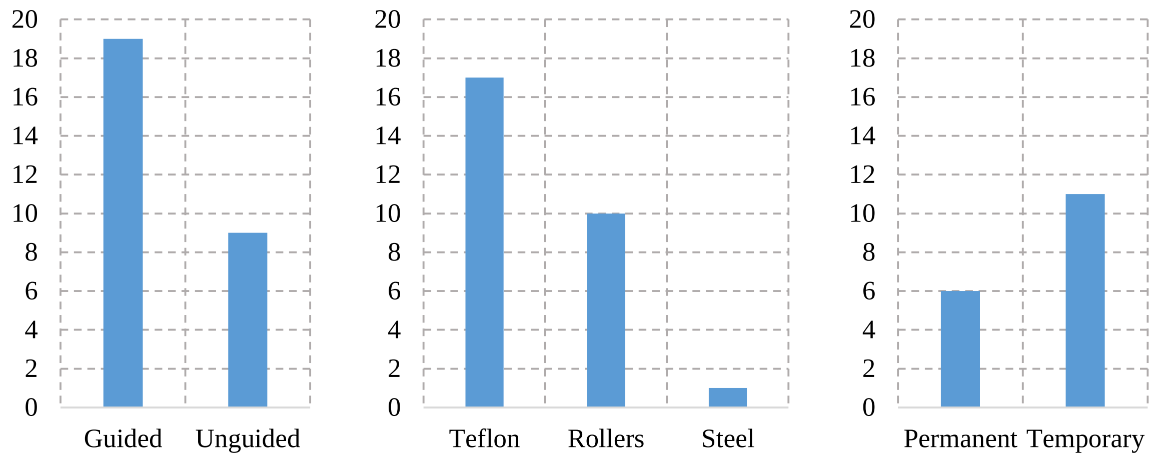
Table 1. Sliding System Specifications from Completed SIBC Projects

#	Name	Location	Span	Span Length	Girder Type	Transverse Restrain	Sliding Surface	Sliding Bearing	Source
1	Ross Clarke Circle Bridge	Alabama	Single	120 ft	Bulb Tee Girder	Guided	Rollers	N.A	SASHTO (2015)
2	Sacaton Bridge	Arizona	Two	140 ft	Bulb Tee Girder	Unguided	Steel Pads	Permanent Bearings	Chase (2016)
3	San Francisco Yerba Buena Viaduct	California	Six	350 ft	Box Girder	Guided	Teflon Pads	Temporary Bearings	Chung et all.(2008)
4	Holbrook Canal Bridge	Colorado	Single	50 ft	Steel I Girder	Guided	Teflon Pads	Permanent Bearings	CDOT (2013), FHWA (2014d)
5	Ft Lyon Canal Bridge	Colorado	Single	85 ft	Side by side box girders	Guided	Rollers	N.A	CDOT (2013), FHWA (2014d)
6	US 34 over Republican River Bridge	Colorado	Single	129 ft	Side by side box girders	Guided	Rollers	N.A	CDOT (2013)
7	Massena Bridge	Iowa	Single	120 ft	Bulb Tee Girder	Guided	Rollers	N.A	Iowa DOT(2013)
8	Milton Madison Bridge	Kentucky & Indiana	Four	2400 ft	Steel Truss	Guided	Teflon Pads	Permanent Bearings	Collins (2013), Bolte (n.d.)
9	US-131 over 3 Mile Road	Michigan	Single	86 ft	Spread Box Beam	Unguided	Teflon Pads	Temporary Bearings	Aktan and Attanayake (2015)
10	M-50 over I-94	Michigan	Two	198 ft	Spread Box Beam	Guided	Teflon Pads	Temporary Bearings	Aktan and Attanayake (2015)
11	M-100 over CN Railroad	Michigan	Single	107 ft	Steel I Girder	Guided	Rollers	N.A	-
12	Larpenteur Avenue Bridge	Minnesota	Two	187 ft	Bulb Tee Girder	Guided	Teflon Pads	Permanent Bearings	Lesch (2015)
13	Gasconade River Bridge	Missouri	Four	670 ft	Steel I Girder	Unguided	Teflon Pads	Temporary Bearings	Haines and Jones (2011)
14	I-15 Bridge	Nevada	Single	160 ft	Bulb Tee Girder	Unguided	Teflon Pads	Temporary Bearings	FHWA (2014b), Searcy et all. (2012), Searcy and Kolkman (2012)
15	I-84 Bridge Over Dingle Road	New York	Single	71 ft	Double Tee Precast	Unguided	Teflon Pads	Temporary Bearings	SHRP 2 R04 (2014), Sivakumar (2014), Bhajandas et all. (2014)
16	Rogue River Bridge	Oregon	Single	307 ft	Concrete Tied Arch	Guided	Rollers	N.A	ODOT (2008)

Table 1 - continued

17	Crossing 3 over Elk Creek	Oregon	Three	207 ft	Steel I Girder	Guided	Teflon Pads	Temporary Bearings	Ardani et all (2010)
18	Crossing 4 over Elk Creek	Oregon	Two	222 ft	Bulb Tee Girder	Guided	Teflon Pads	Temporary Bearings	Ardani et all (2010)
19	OR 213 Bridge over Washington St.	Oregon	Single	130 ft	Steel I Girder	Guided	Rollers	N.A	ODOT(2010)
20	I-80 over Echo Dam Road	Utah	Single	130 ft	Bulb Tee Girder	Unguided	Teflon Pads	Temporary Bearings	Boyle (2011), Arens and Jaynes (2012)
21	I-80 at 2300 E	Utah	Single	135 ft	Bulb Tee Girder	Guided	Teflon Pads	Permanent Bearings	Arens and Jaynes (2012)
22	I-80 at Summit Park	Utah	Single	180 ft	Steel I Girder	Unguided	Teflon Pads	Temporary Bearings	Arens and Jaynes (2012)
23	I-80 at Wanship	Utah	Single	140 ft	Steel I Girder	Unguided	Teflon Pads	Temporary Bearings	FHWA (2014c)
24	SR 201 Bridge	Utah	Single	-	Steel I Girder	Unguided	Teflon Pads	Temporary Bearings	Hansen (2015)
25	Hood Canal Bridge West Approach	Washington	Single	154 ft	Bulb Tee Girder	Guided	Rollers	N.A	Merth (2008)
26	Hood Canal Bridge East Approach Spans	Washington	Five	609 ft	Bulb Tee Girder	Guided	Rollers	N.A	Merth (2008)
27	North East 8th Street Bridge	Washington	Two	328 ft	Steel I Girder	Guided	Rollers	N.A	Lem and Kayle (n.d.)
28	Dundas Street Bridge	Ontario	Three	600 ft	Steel Box Girder	Guided	Teflon Pads	Permanent Bearings	Anderson and Trankler (1991) Anderson and Trankler (1996)

Guided systems are more favorable than unguided systems. The use of Teflon pads is more common than rollers. A steel-to-steel sliding surface is also used; however, performance was not found favorable. Most of the time, slide is completed on temporary bearings. This is followed by vertical jacking to remove temporary bearings and place with permanent bearings. Distribution of implemented slide systems are shown in Figure 15.



(a) Types of transverse restraints

Types of sliding surfaces

(c) Types of sliding bearings

Figure 15. Sliding system components distribution of completed SIBC projects

Utilizing guided sliding systems generally result in a smooth slide without a noticeable challenge related to the guided system. Guided systems with Teflon pads and rollers cause binding in some cases. Guided systems prevent drifting of the superstructure since movement in the transverse direction is limited by constraints. This orientation may results in binding due to a development of large transverse forces; this can possibly cause damage to the substructure since it is generally not designed for transverse forces. On the other hand, unguided systems result in drifting as a result of not having a restraint in the transverse direction. Being unrestrained prevents force development in the transverse direction; however, 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. Fortunately, these situations are controllable with suggestions proposed in this study.

Transverse forces should be considered in the design of the temporary and/or permanent substructure in the uses of guided systems. Adequate tolerances should be provided to prevent the superstructure from falling off the track in unguided systems. Moreover, displacement

differences more than 2 in should be corrected. Unguided systems should include a transverse jacking system to use in case an excessive displacement occurs in the transverse direction. Most importantly, displacement of the superstructure should be monitored and recorded to anticipate potential incidents. Monitoring allows taking necessary precautions on time and ensures safe, smooth and fast sliding. Guided and unguided system examples from completed SIBC implementations are shown in Figure 16.

(a) Unguided system (I-80 over Echo Dam Road, UTAH) | (b) Guided system with rollers (Lyon Canal Bridge, Colorado) | (c) Guided system with Teflon Pads (M-50 Bridge over I-96, Michigan)

Figure 16. Guided and Unguided systems

Three sliding surface designs are documented in completed SIBC implementations. Teflon pads generally provide smooth sliding. However, several design aspects should be considered to assure smooth sliding with Teflon pads: First, thickness of the Teflon pads should be adequate to prevent excessive deformations. Larger size pads can be specified to reduce the bearing pressure. Reuse of pads should be avoided. Use of lubricant with pads is suggested. However, amount should be limited. Excessive use often results in leakage of lubricant under the pads causing stability problems. Dimpled Teflon pads are suggested to provide space for the lubricant to collect.

The coefficient of friction of Teflon sliding surfaces can vary from 5% to 20% depending on mainly bearing pressure and sliding velocity. Friction literature is described in Chapter 2. Pretesting is recommended to investigate specific pads utilized in the sliding system in order to reduce uncertainties. In addition, a test slide is significantly important not only to overcome the breakaway friction but also to understand the level of resistance of the sliding system for that particular application.

Rollers generally provide smooth sliding, yet some key aspects should be taken into consideration. Low friction in rollers is an advantage but can be a challenge under certain situations. With low coefficient of friction an emergency stopping mechanism should be

provided with an actuating system to handle unexpected forces (such as wind). Wind depending on direction may also result in a sudden increase in sliding forces. An actuating system with a combined pulling and pushing capability is also recommended. In addition, rollers apply high concentrated loads which may cause deflections of the sliding track. Concentrated forces and deflection limitations should be considered in the design of the temporary and permanent substructure as well as the transition zone. Steel pads are not recommended because of the large frictional resistance. Although large friction has some advantages, utilizing Teflon pads or rollers in a properly designed sliding system is much more favorable.

Sliding the superstructure on permanent bearings is also possible when Teflon pads are used. Vertical jacking following sliding is eliminated with utilizing permanent bearings in the slide. Vertical jacking is required with temporary bearings or rollers. Large tensile stresses can develop on the superstructure and may lead to cracking during vertical jacking. In addition, in the use of temporary or permanent bearing friction, transfer is critical. Teflon pads should be restrained appropriately and lubricants should be used carefully with dimpled pads. Otherwise stability problems can be developed which may interrupt the sliding or even damage the bearings or structure. This situation is observed in the slide of the US 131 Bridge over 3 Mile Road. Besides, Teflon pads were displaced with superstructure because of insufficient restraint in sliding direction. Used Teflon pads were not dimpled. Lubrication was squeezed off the surface and lubricants got between Teflon pads and railing girder. Also, permanent bearing and Teflon pad damage occurred during the M-50 Bridge over US I-96 slide because of the grimy sliding track and mismatch of permanent bearing and Teflon Pad restraints (MDOT 2015). Both challenges experienced in the US 131 and M-50 Bridge are shown in Figure 17.

(a) Temporary bearing stability problem in US 131 Bridge over 3 Mile Road

(b) Damage caused by grimy sliding track and restraint mismatch in M-50 Bridge over I-96

Figure 17. Sliding bearing challenges (Source: MDOT, 2015)

In general, it is important to provide detailed information about the sliding system in the bridge plans. A contingency plan includes precautions for sliding-system related challenges. In all cases, monitoring significantly increases the safety and quality and reduces the time duration of the slide.

Actuating Systems

Actuating systems are classified according to movement control mechanism, actuation method, and utilized actuation device. There are two ways to regulate the movement to maintain the applied pressure. Pressure regulated systems are capable of controlling only the hydraulic pressure applied to the jack. Whereas servo controlled systems monitor displacements and calibrate applied pressure automatically to balance the movement. Pressure in each abutment or bent is synchronized and automatically corrected to ensure equal displacements. Servo controlled systems maintain an aligned sliding since difference of friction resistance is balanced with controlling the applied pressure. In addition, actuating can be performed either by pushing the bridge with rams or by pulling the cables or bars attached to the superstructure with prestressing jacks. Actuation methods are visualized in Figure 7. The classification approach to the actuating systems is shown in Figure 18.

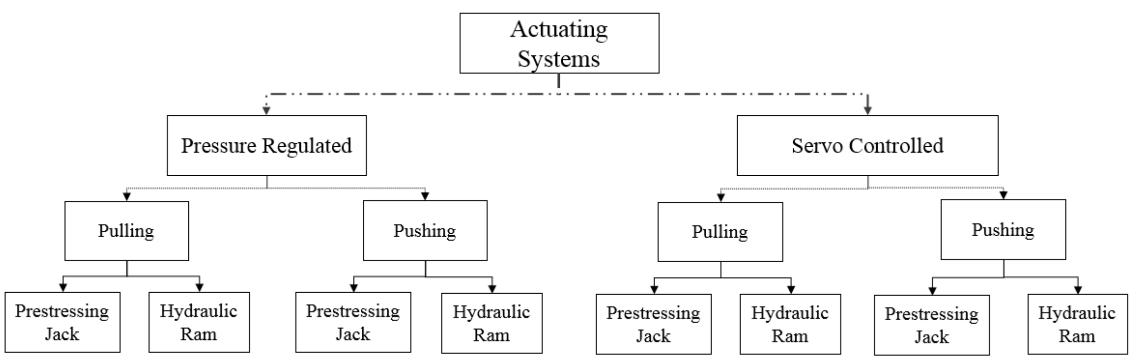


Figure 18. Classification approach for actuating systems

Classifications of actuating system components of completed implementations are summarized in Table 2. Actuation control mechanisms, methods, and devices of each completed SIBC project are listed.

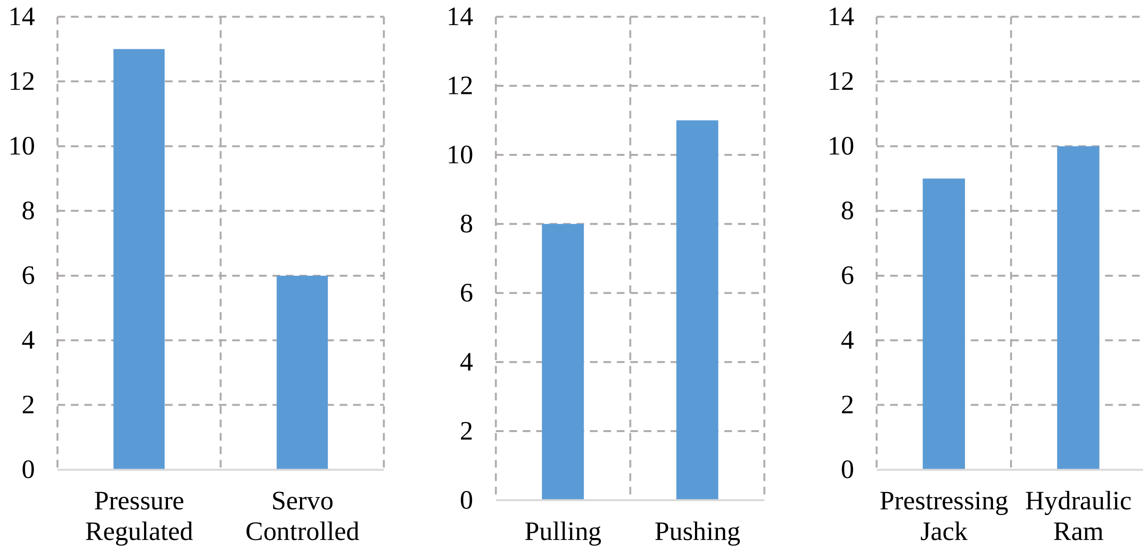
Table 2. Actuating System Specifications from Completed SIBC Projects

#	Name	Location	Span	Span Length	Girder Type	Actuation Control Mechanism	Actuation Method	Actuation Device	Source
1	Sacaton Bridge	Arizona	Two	140 ft	Bulb Tee Girder	Pressure Regulated	Pulling	Prestressing Jack	Chase (2016)
2	Holbrook Canal Bridge	Colorado	Single	50 ft	Steel I Girder	Pressure Regulated	Pushing	Hydraulic Ram	CDOT (2013), FHWA (2014d)
3	Ft Lyon Canal Bridge	Colorado	Single	85 ft	Side by side box girders	Pressure Regulated	Pulling	Prestressing Jack	CDOT (2013), FHWA (2014d)
4	US 34 over Republican River Bridge	Colorado	Single	129 ft	Side by side box girders	Pressure Regulated	Pushing	Hydraulic Ram	CDOT (2013)
5	Massena Bridge	Iowa	Single	120 ft	Bulb Tee Girder	Servo Controller	Pulling	Prestressing Jack	Iowa DOT(2013)
6	US-131 over 3 Mile Road	Michigan	Single	86 ft	Spread Box Beam	Pressure Regulated	Pulling	Prestressing Jack	Aktan and Attanayake (2015)
7	M-50 over I-94	Michigan	Two	198 ft	Spread Box Beam	Pressure Regulated	Pushing	Hydraulic Ram	Aktan and Attanayake (2015)
8	M-100 over CN Railroad	Michigan	Single	107 ft	Steel I Girder	Servo Controller	Pushing	Hydraulic Ram	-
9	Larpenteur Aveneu Bridge	Minnesota	Two	187 ft	Bulb Tee Girder	Pressure Regulated	Pushing	Hydraulic Ram	Lesch (2015)
10	Gasconade River Bridge	Missouri	Four	670 ft	Steel I Girder	Servo Controller	Pushing	Hydraulic Ram	Haines and Jones (2011)
11	I-15 Bridge	Nevada	Single	160 ft	Bulb Tee Girder	Pressure Regulated	Pushing	Hydraulic Ram	FHWA (2014b), Searcy et all. (2012), Searcy and Kolkman (2012)
12	I-84 Bridge Over Dingle Road	New York	Single	71 ft	Tee Precast	Pressure Regulated	Pushing	Hydraulic Ram	SHRP 2 R04 (2014), Sivakumar (2014), Bhajandas et all. (2014)
13	I-80 over Echo Dam Road	Utah	Single	130 ft	Bulb Tee Girder	Pressure Regulated	Pushing	Hydraulic Ram	Boyle (2011), Arens and Jaynes (2012)
14	I-80 at 2300 E	Utah	Single	135 ft	Bulb Tee Girder	Pressure Regulated	Pushing	Hydraulic Ram	Arens and Jaynes (2012)
15	I-80 at Wanship	Utah	Single	140 ft	Steel I Girder	Pressure Regulated	Pushing	Prestressing Jack	FHWA (2014c)

Table 2 - continued

16	Hood Canal Bridge West Approach	Washington	Single	154 ft	Bulb Tee Girder	Servo Controller	Pulling	Prestressing Jack	Merth (2008)
17	Hood Canal Bridge East Approach Spans	Washington	Five	609 ft	Bulb Tee Girder	Servo Controller	Pulling	Prestressing Jack	Merth (2008)
18	North East 8th Street Bridge	Washington	Two	328 ft	Steel I Girder	Pressure Regulated	Pulling	Prestressing Jack	Lem and Kayle (n.d.)
19	Dundas Street Bridge	Ontario	Three	600 ft	Steel Box Girder	Servo Controller	Pulling	Prestressing Jack	Anderson and Trankler (1991) Anderson and Trankler (1996)

Pressure regulated systems are used more commonly than servo controlled ones. Combined pulling and pushing methods are utilized multiple times. Prestressing jacks are used with the pulling method only with one exception: where it is used as a mechanism in the pushing method. Hydraulic rams are used with the pushing type of actuation in all documented SIBC projects. Distributions of use of systems are shown in Figure 18.



(a) Types of actuation control mechanisms (b) Types of actuation methods (c) Types of actuation devices

Figure 19. Actuating system parameters distribution of completed SIBC projects

A servo-controlled mechanism is utilized in limited number of projects. Pressure regulated actuating faces a differential friction result with drifting of the superstructure. Drifting delays the sliding and increases the time duration of the slide. One example was the I-15 Bridge in Nevada. This project included a two-bridge replacement. The first bridge was slid without major problems in 75 minutes while the second slide took 300 minutes to be completed due to drifting of the superstructure (Searcy and Kolkman 2012). Drifting did not result in damage to the structure in any project. However, the actuating system had been damaged in the slide of the I-84 Bridge over Dingle road according to SHRP (2014). It is difficult to restore bridge alignment after the drifting initiates. Actuating from only one side to counter drift the superstructure is one solution. Performing vertical jacking and realigning the superstructure is another common solution utilized.

On the other hand, servo controlled actuating systems provide much more stable alignment. Features enable force and displacement monitoring during the slide. Multiple controllers can be synchronized to achieve equal force or displacement. For instance when a servo controlled system detects a differential displacement, applied forces are immediately modified to provide equal movement to keep the alignment. Maximum limits can be defined for force and displacement in order to prevent excessive pressure development in case of binding. Operation is automatically aborted immediately when defined maximum limits are reached. Well-designed servo controlled systems eliminate complications due to differential friction and movement. The Dundas Street Bridge slide is one of the successful examples of utilizing a servo controlled mechanism. Differential displacements were kept below 1 in. with a servo controlled actuating system, and the slide was performed without any delays (Anderson and Trankler 1991).

Actuating system selection should be suitable with the selected slide system. Servo controlled systems should be utilized with unguided slide systems to eliminate the effects of differential friction resistance. Pressure regulated systems should be only used with guided slide systems with attentive visual monitoring of movement and a contingency plan.

The actuation method is defined based on the direction of the applied forces. Forces are applied by utilized actuation devices. Therefore, actuation methods are evaluated together with actuation devices described in Chapter 2.

Pushing actuation systems utilize hydraulic rams. A ram piston is connected through a clevis or a swivel to end diaphragms in concrete bridges and bearing stiffeners in steel bridges. If there is skew in the bridge, diaphragm design should be modified to consider the capacity for the load developed by the actuating system. Swivel connections should be utilized in the connection of the piston and diaphragms to provide tolerances in the connection especially in bridges with a skew. The connection between rams and the sliding track is achieved with removable pins, dog plates or ram ears in different projects (Figure 20). Spacing between connections within the sliding track is a ratio proportional to ram stroke length. However, generally it is not possible to utilize the full stroke during each pushing cycle. As a result matching the connection points becomes a challenge.

(a) Removable pins (M-100 Bridge over CN Railroad, Michigan)   (b) Dog plate (Larpenteur Bridge, Minnesota)   (c) Ram Ears (I-15 Bridge, Nevada)

Figure 20. Different connections between hydraulic ram and sliding track

Complete actuating systems developed by Enerpac and Mammoet utilize a self-retracting mechanism. These systems automatically reposition rams within guided sliding systems. It is possible to achieve much faster and smoother actuation with those systems.

(a) Mammoet skidding system (Source : Mammoet website)   (b) Enerpac sharktooth jacking track system (Source: Enerpac website)

Figure 21. Self-retracting mechanisms

The pulling method utilizes prestressing jacks and cables or rods. One end of cable is rigidly connected to the end diaphragm or sliding girder, which is placed under the end diaphragms. A sliding girder can be utilized temporarily to prevent direct application of forces to the superstructure. Prestressing jacks are placed at the other end of the cable, and jacking reaction frames are utilized for the bearing purposes of strand jacks. Actuating forces are transferred with jacks to the cable, and the cable pulls the superstructure. Cables are released and jacks are retracted after each pulling cycle. Prestressing jacks do not require a connection to the railing girder. As a result, retracting is generally faster than hydraulic rams. However, cables are not as stiff as rams. Actuation forces elongate the cable, which results with a loss in stroke length and jerk in movement due to flexibility of the cable.

There are many different orientations used with prestressing jacks, cables and reaction frames in completed SIBC projects. The Northeast 8th Street Bridge in Washington utilizes a brake rod since the pulling operation is performed uphill. Returnwalls of the abutments were used as a reaction frame in many cases. Temporary reaction frames were constructed when returnwalls were not available to use. Cables were used to connect reaction frames and the superstructure. Prestressing jacks were generally connected to the reaction frame (Figure 22a). Cables transferred pulling forces to the superstructure. Moreover, jacks were connected to push the superstructure. In addition, in some projects for example, the I-80 Bridge slide utilized prestressing jacks and cables to push the superstructure (Figure 22b). Cables are anchored to a concrete block and placed inside a duct in the end diaphragm. Jacks are attached to the other side of the diaphragm, and the bridge is used as the reaction frame.

(a) Massena Bridge, Iowa (b) I-80 Bridge at Wanship, Utah

Figure 22. Prestressing jack application

Hydraulic pressure is used as a source of applied forces in every application. The capacity and the stroke length of the jacks are important. Capacity is selected based on the force required to maintain the sliding. The required sliding force required is proportional to the coefficient of friction and weight of the superstructure. Completed projects show that specified jack capacities are between 30 and 110T. It is suggested to have a minimum number of actuation points with maximum actuation force to minimize synchronicity problems. On the other hand, specified stroke lengths for jacks were between 2 to 40 in. Long stroke lengths are not recommended because unidentified binding can become a bigger problem if it occurs early during the actuating cycle. On the other hand, very short stroke lengths can increase the slide duration significantly. It is recommended to select the stroke length according to tolerances of the actuating systems. In addition, 4 to 24 in./min velocities are recorded in completed projects.

Temporary Structure

Temporary structures are classified according to orientation and connection of systems between temporary and permanent locations. Orientations are classified as inline and infront which are described in Chapter 2. Moreover, inline and infront systems have different connection mechanisms. Temporary support structures carry the weight; they also carry actuating forces in the direction of sliding and drifting forces in the direction transverse to sliding. These forces may be transferred to permanent abutments by provided connections. Deformations in these systems are significantly critical for the quality of slide since discontinuities resulting from deformations can dramatically the sliding resistance uniformity as well as generate binding situations. The classification approach of support systems is shown in Figure 23.

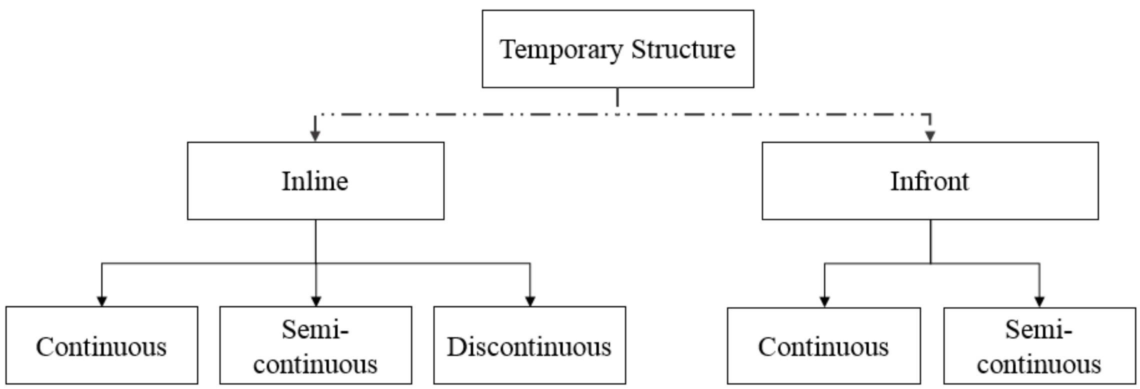


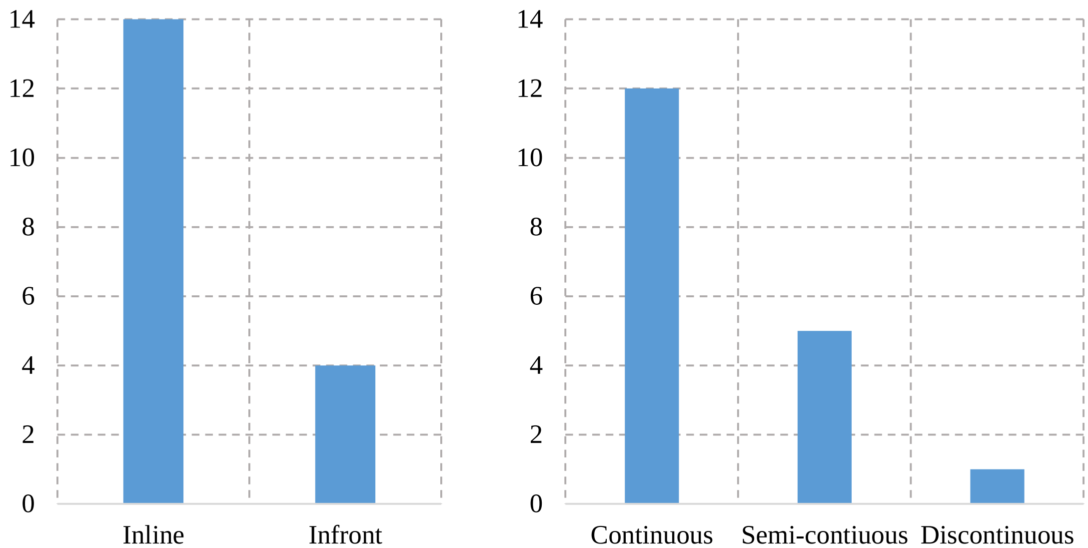
Figure 23. Classification approach for support systems

Classifications of temporary sliding support structures of completed implementations are summarized in Table 3. Orientation of support structures and the connection type of each completed SIBC project is listed.

Table 3. Temporary Structure Specifications from Completed SIBC Projects

#	Name	Location	Span	Span Length	Type	Structure Orientation	Connection Type	Source
1	Sacaton Bridge	Arizona	Two	140 ft	Bulb Tee Girder	Inline	Continuous	Chase (2016)
2	Holbrook Canal Bridge	Colorado	Single	50 ft	Steel I Girder	Inline	Semi-continuous	CDOT (2013), FHWA (2014d)
3	Ft Lyon Canal Bridge	Colorado	Single	85 ft	Side by side box girders	Inline	Semi-continuous	CDOT (2013), FHWA (2014d)
4	US 34 over Republican River Bridge	Colorado	Single	129 ft	Side by side box girders	Infront	Semi-continuous	CDOT (2013)
5	Massena Bridge	Iowa	Single	120 ft	Bulb Tee Girder	Inline	Continuous	Iowa DOT(2013)
6	Milton Madison Bridge	Kentucky & Indiana	Four	2400 ft	Steel Truss	Inline	Continuous	Collins (2013), Bolte (n.d.)
7	US-131 over 3 Mile Road	Michigan	Single	86 ft	Spread Box Beam	Infront	Continuous	Aktan and Attanayake (2015)
8	M-50 over I-94	Michigan	Two	198 ft	Spread Box Beam	Inline	Semi-continuous	Aktan and Attanayake (2015)
9	M-100 over CN Railroad	Michigan	Single	107 ft	Steel I Girder	Inline	Continuous	-
10	Gasconade River Bridge	Missouri	Four	670 ft	Steel I Girder	Inline	Semi-continuous	Haines and Jones (2011)
11	Larpenteur Aveneu Bridge	Minnesota	Two	187 ft	Bulb Tee Girder	Inline	Continuous	Lesch (2015)
12	I-84 Bridge Over Dingle Road	New York	Single	71 ft	Tee Precast	Inline	Discontinuous	SHRP 2 R04 (2014), Sivakumar (2014), Bhajandas et all. (2014)
13	Rogue River Bridge	Oregon	Single	307 ft	Concrete Tied Arch	Inline	Continuous	ODOT (2008)
14	Crossing 3 over Elk Creek	Oregon	Three	207 ft	Steel I Girder	Infront	Continuous	Ardani et all (2010)
15	Crossing 4 over Elk Creek	Oregon	Two	222 ft	Bulb Tee Girder	Infront	Continuous	Ardani et all (2010)
16	I-80 over Echo Dam Road	Utah	Single	130 ft	Bulb Tee Girder	Inline	Continuous	Boyle (2011), Arens and Jaynes (2012)
17	I-80 at 2300 E	Utah	Single	135 ft	Bulb Tee Girder	Inline	Continuous	Arens and Jaynes (2012)
18	Dundas Street Bridge	Ontario	Three	600 ft	Steel Box Girder	Inline	Continuous	Anderson and Trankler (1991) Anderson and Trankler (1996)

Use of inline temporary supports with the permanent substructure is more common than utilizing infront temporary support. Connections of inline systems can be continuous which transfers all the forces and moments; semi-continuous which can transfer only some force components and moments; and discontinuous without any load transfer. Infront systems are generally continuous with a full load transfer; however, in some cases a semi-continuous connection is used by prohibiting moment transfers by hinge connection. Distributions are shown in Figure 24.



(a) Temporary support system (b) Connection mechanism

Figure 24. Support system and connection mechanism of completed SIBC projects

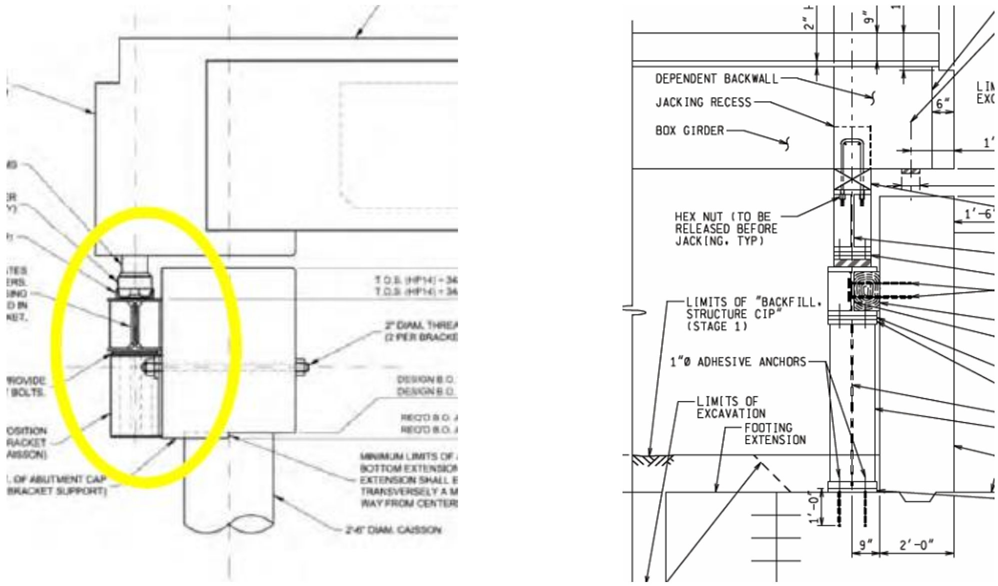
When temporary support systems are evaluated, there are certain design considerations whether the inline or infront type of support system is selected. Outcomes of some completed projects show that a significant amount of force is transferred to the substructure as a result of the slide. Force development in the transverse direction of sliding is generally disregarded in the design, yet field observations and sliding monitoring studies showed that forces develop in the transverse direction of sliding. Forces develop at the sliding surface are directly transferred to the temporary support structure. During the slide of the M-50 Bridge over I-94, monitoring indicated forces up to 13% and up to 7% of the bridge weight were calculated in the direction of slide and transverse to slide respectively (Attanayake et al. 2016). In addition, superstructure acceleration data recorded during to lateral bridge slide of the M-100 Bridge over CN Railroad shows that forces up to 6% of the weight were

measured in the direction of sliding as well as the transverse direction. These forces must be taken into consideration in the design of a temporary support system.

Relative deflections of the railing girder should also be limited. Deflections affect the interaction of the sliding surfaces. Bearing pressure may be increased or decreased which may cause changes in friction resistance. Change in friction may result in binding of the superstructure. Differential deflections occur between the supports and span locations of one of the temporary supports. Binding is also possible when stiffness of the two temporary supports are unequal. In order to prevent stiffness related binding problems, first stiffness of the temporary support should be high enough to minimize the relative deflections of the temporary support; and second stiffness for all temporary supports along each abutment should be about equal. It is recommended to have the falsework design engineer in the field to inspect the design and build in conditions of the temporary support system to make sure that relative deflections are not developing.

It is also recommended that a moving load analysis is performed for the temporary support system considering forces developed in the direction of gravity, sliding and transverse of sliding. Furthermore, if the traffic is shifted to the new superstructure while on the temporary location, a traffic live load analysis should be performed.

In addition to general considerations, eccentric loads can develop on the permanent substructure when infront temporary support system is utilized. A segment of the temporary support may be connected to the permanent substructure on the permanent location of the superstructure. Using the foundation of the permanent abutment to support the temporary support system and connecting railing girder to the abutment cap in the permanent location are the two examples documented among completed projects (Figure 25). This results with transfer of superstructure and sliding loads to the permanent substructure eccentrically. Eccentric loading should be considered when infront temporary support system is connected to the permanent substructure along the permanent alignment.



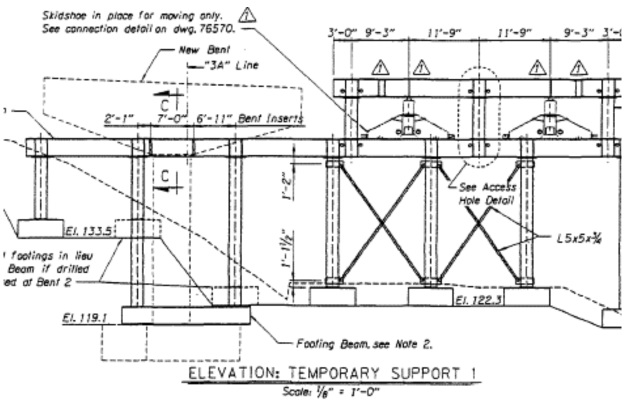
(a) Connection of railing girder to permanent abutment cap
(US-34 Bride over Republican River, Colorado)

(b) Connection of temporary columns to permanent foundation
(US-131 Bridge over 3 Mile Road, Michigan)

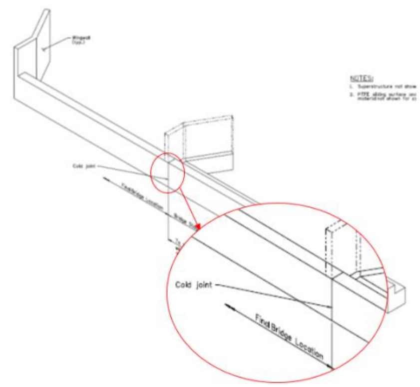
Figure 25. Connection of infront temporary supports to permanent substructure

Connection between a temporary support system and permanent substructure is important when inline type is selected. Types of connections utilized are listed in Figure 24b and displayed in Figure 26. Axial forces, shear forces and moments can be transferred through the connection when the temporary support is continuous. Bolts are the most common method 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. Semi-continuous connections limit load transfer in some directions. Use of cold joint, hinges, and solid grout are observed and classified as semi-continuous connections. For example, a hinge connection was implemented for an infront temporary support on the US 131 Bridge over 3 Mile Road. However, a deflection check was not performed in the design. Continuity of the connection was a question before sliding due to potentially large rotations at the hinge locations. As a solution, additional supports were installed and welded. The connection was transformed to continuous (Aktan and Attanayake 2015). Moreover, in some cases, a temporary structure is cast against a permanent substructure to prevent load transfer in all directions. A discontinuous connection is not recommended since excessive deformations in the temporary support system may cause damage to the permanent substructure. Discontinuous connections generally result in differential deflections at the connection which prevents smooth

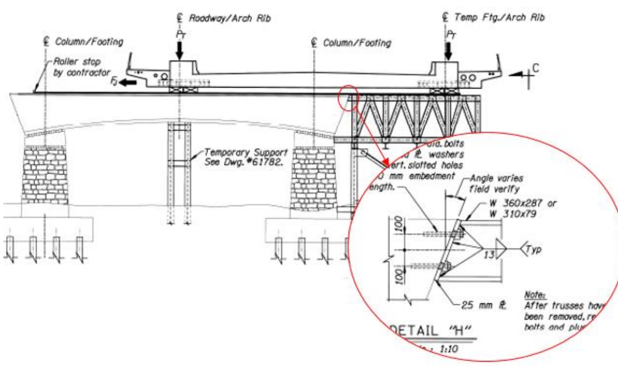
transition resulting with an increase in sliding resistance. For example, a discontinuous connection on the Larpenteur Avenue Bridge, Minnesota slide caused deformation in permanent abutments (Lesch 2015). Compression forces were applied from the temporary structure to the permanent substructure as a result of the deformations in the temporary structure in the sliding direction.



(b) Infront supports with continuous connection



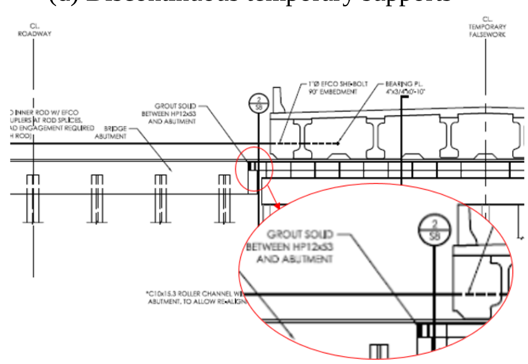
(a) Connection with cold joint



(c) Connection with bolts

(d) Discontinuous temporary supports

(f) Connection with hinges



(g) Connection with solid grout

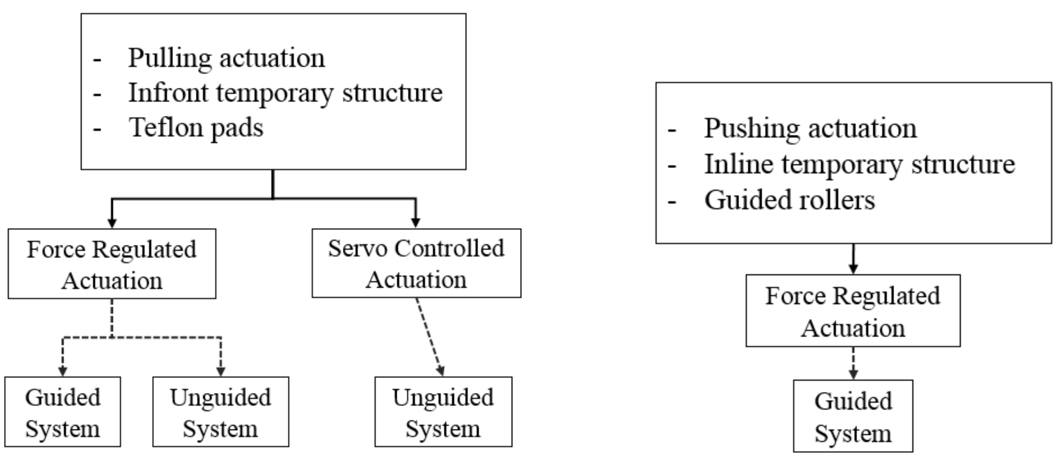
Figure 26. Different connection types in temporary support systems

Finite Element Simulations

Finite element simulations are developed to mathematically demonstrate the effects of the selection of slide, actuating and temporary structure. Abaqus/Explicit solver was used in simulations. Two completed SIBC in Michigan were selected as case studies: the US 131 Bridge over 3 Mile Road and the M-100 Bridge over CN Railroad.

The US 131 Bridge over 3 Mile Road consisted of two bridge replacements. An unguided slide system with Teflon pads and a force regulated, pulling actuating system with 2 in. stroke length, along with an infront temporary support structure were utilized as a complete lateral slide system. Several modifications were done in the second bridge replacement of the US-131 Bridge in order to decrease the challenges experienced in the first slide. An unguided sliding system was transformed to a guided system one by adopting side rollers. Both cases are simulated. Effects of differential friction and differential alignment of the railing girder were also investigated. Simulations are also repeated by adopting a servo controlled actuating system.

The M-100 Bridge over CN Railroad was a 52° skewed bridge replacement. Guided rollers, a servo controller, and a pushing actuating system with 40 in. stroke length, along with inline temporary supports, were utilized.



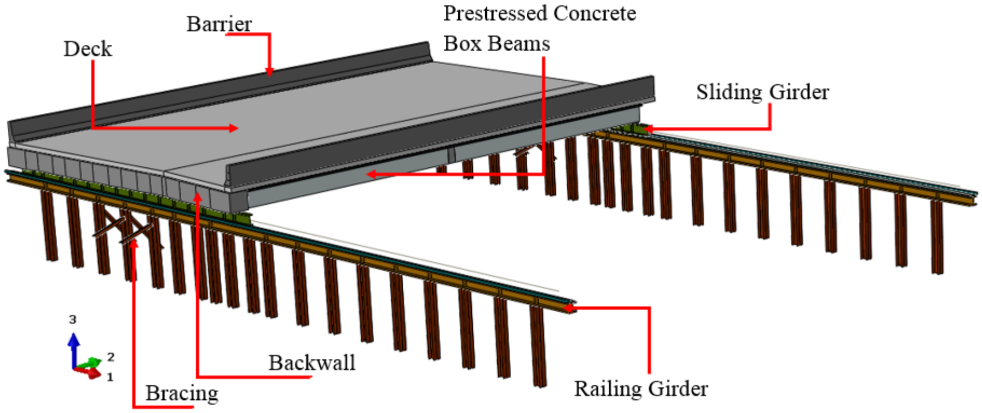
(a) Simulation scheme of US-131 Bridge over 3 Mile road

(b) Simulation scheme of M-100 Bridge over CN Railroad

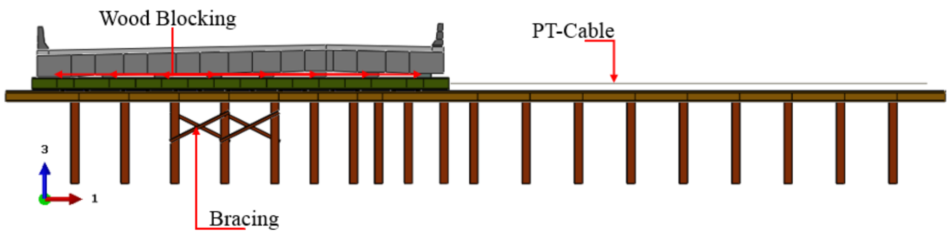
Figure 27. Developed simulations for evaluation

Simulations of Lateral Slide with Pulling Type of Actuation and Infront Temporary Structure

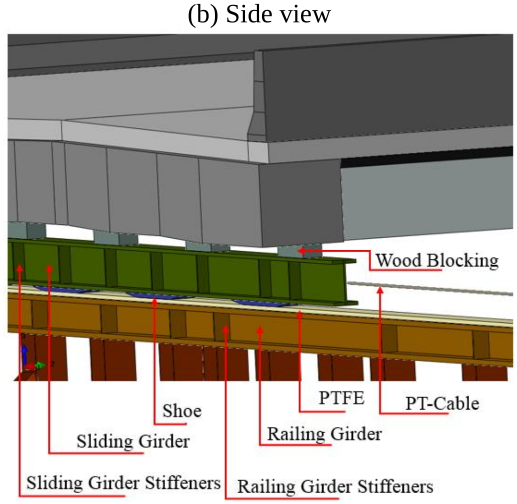
The US-131 Bridge over 3-Mile Road was modelled to develop simulations with a pulling type of actuation and an infront temporary structure. Simulations included pressure regulated and servo controlled actuating as well as guided and unguided sliding systems. Effects of equal and differential friction were also investigated. Geometry and components of the bridge are shown in Figure 28.



(a) Isometric view



(b) Side view



(c) A close up view of sliding and railing girder details

Figure 28. Geometry and components of an FE Model with pulling type of actuation and infront temporary supports

Bridge plans were used to develop the realistic finite element model geometry and material properties. Bridge geometry was modeled with 3D-Solid elements, except the cables which were modeled with truss elements. The bridge superstructure was discretized in a coarse mesh since superstructure stresses are not the primary focus. The components of the lateral slide system discretization were more refined. The base of the piles in the temporary structure is defined fixed in all degrees of freedom, and the far end of the cable is restrained in all directions other than the sliding direction.

Contact interaction was defined between each temporary sliding shoe and Teflon pads with the contact pair feature of analysis platform (Abaqus 2015). Frictionless contact surfaces were defined between sliding shoes and transverse restraints in guided models. The Coulomb friction model was defined and assigned to contact pairs. Friction parameters are listed as static friction, kinetic friction and decay rate in the Coulomb model. Friction values and decay rate were defined from the frictional properties of Teflon pads. An average contact pressure of 282 psi was calculated under each sliding shoe assuming the superstructure weight is equally and uniformly distributed to each shoe. Friction coefficients of 10% static and 5 to 2% kinetic were adopted at interaction for Teflon Pads (MDOT 2014). The decay rate is defined as 0.4105 while decreasing the friction from 10% to 5% when the slip rate achieves 10 in/s, which was the velocity defined for simulations. Coefficient of friction developed versus the slip-rate, according to the Coulomb Friction Theory, are shown in Figure 29.

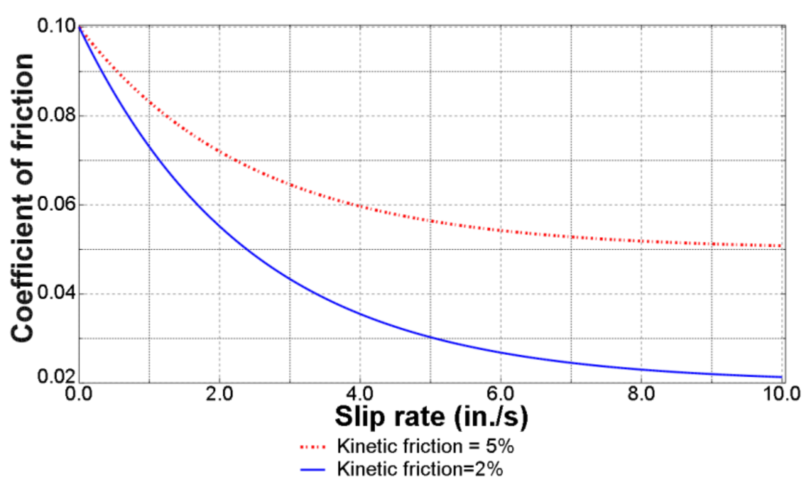


Figure 29. Coefficient of friction model used in US-131 simulations

Pressure Regulated Guided and Unguided System

Forces greater than friction resistance are applied at the far end of the cables with a ramp amplitude in order to simulate a force regulated actuating system. Net force, which is the difference between applied force and friction force, actuates and maintains the sliding. The relationship between applied, friction and net force is shown in Figure 30. Transverse restraints were not incorporated in models with an unguided system while lateral restraints with 2 in. tolerance were incorporated with the guided system.

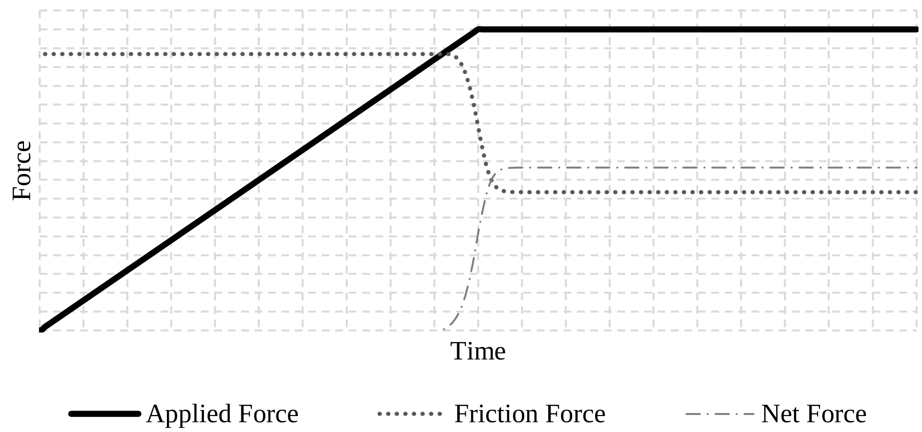


Figure 30. Relationship between the forces acting on Lateral Slide System

Models without transverse restraints, and equal friction is defined at each rail in initial simulations. Forces developed in the sliding direction during one discrete pulling event in pressure-regulated simulations were calculated, and a typical response is shown in Figure 31. According to results, friction forces are proportional with the applied forces until applied forces reach the value of static friction force which is 10% of the bridge weight. As soon as applied forces exceeded the friction forces and velocity starts to increase, friction forces decrease according to the Coulomb friction model. Friction force stabilized after reaching the kinetic stage, which resulted in constant sliding friction force. Removal of the applied force decreases the velocity. As velocity decreases the increase in friction force decelerated and eventually stopped the superstructure. After the movement was stopped, dynamic forces developed.

The calculated sliding forces developed at contact, and reaction forces developed at the base of the temporary structure are shown in Figure 31. Reaction forces showed the same

trend with friction forces until the dynamic stage. Inertia of the temporary supports increases dynamic forces developed at the base of temporary supports. Maximum friction force amplitude was 3.3% of the weight at sliding surface and 8% of the weight at the base of the temporary structure.

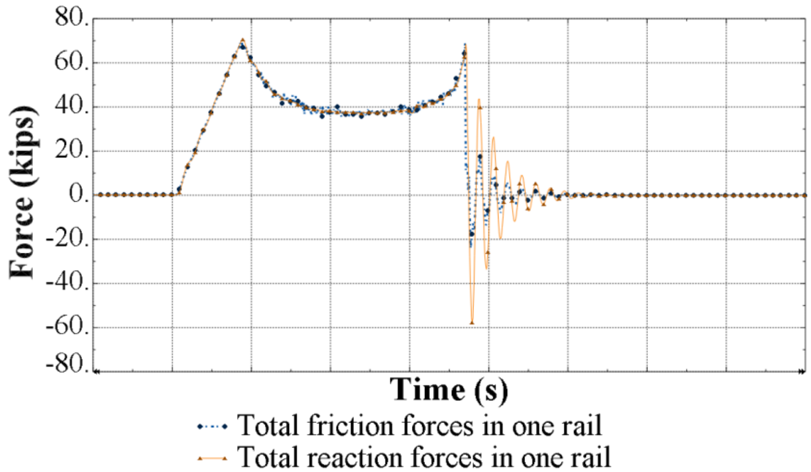
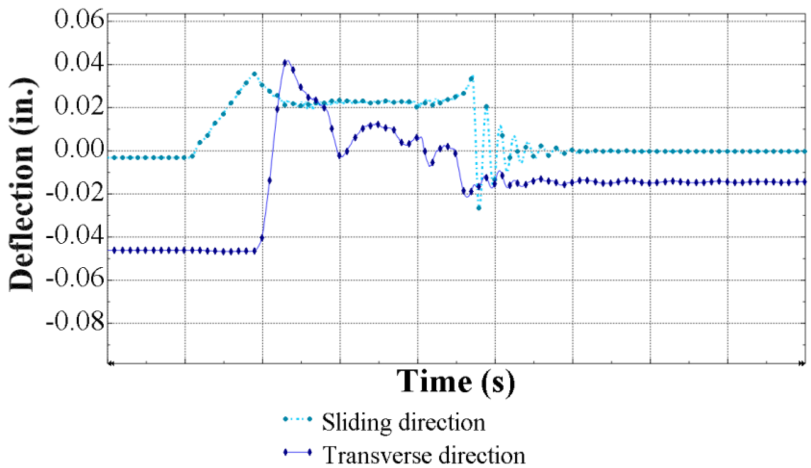
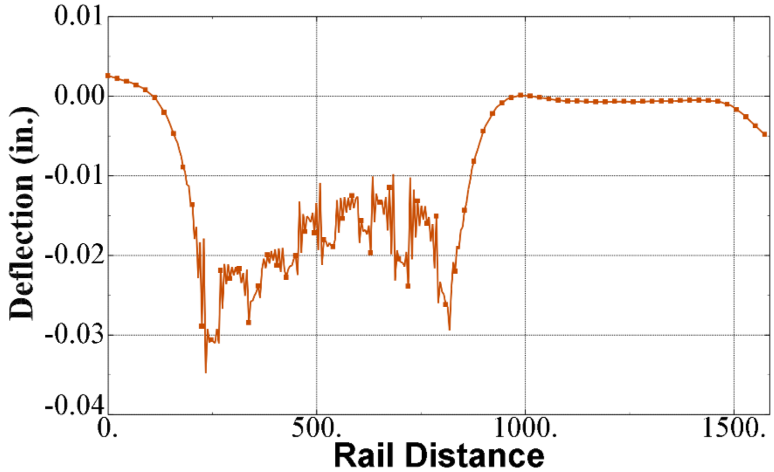


Figure 31. Forces developed in sliding direction in pressure regulated equal friction simulation

Temporary structure deflections are important because of their effects on contact surfaces. The coefficient of friction changes with bearing pressure, and temporary structure deflections can affect the contact continuity which may result in a change of friction. Temporary structure deflection at the tip of the rails were calculated and shown in Figure 32a. Displacement at the rail tips is expected to be higher since no restraint is provided at the cantilever end. In addition, deflections due to weight along the rails at the end of the pushing cycle in the direction of gravity were plotted in Figure 32b. Deflections were calculated equal in both rails since friction was assumed constant. Maximum deflection in the gravity direction was calculated as 0.035 in. Maximum deflections in sliding and transverse direction were calculated 0.035 in. and 0.042 in. respectively. The largest deflections are calculated in the transverse direction despite having zero forces in the transverse direction. Transverse deflections were developed due to gravity forces and low stiffness in that direction.



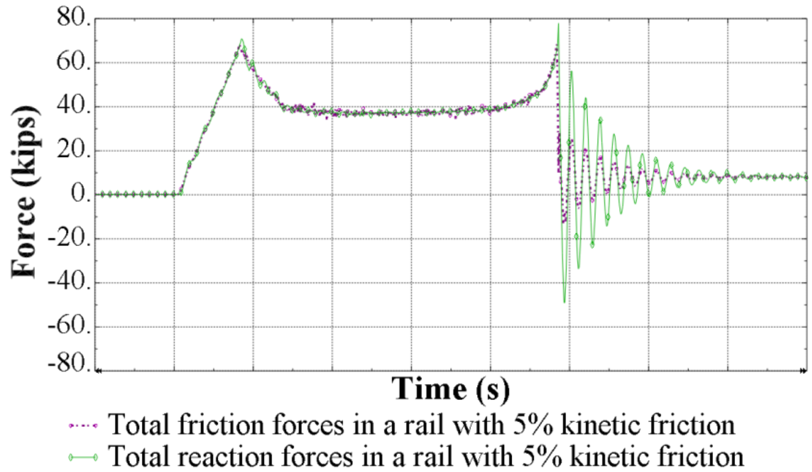
(a) Tip deflections due to sliding forces



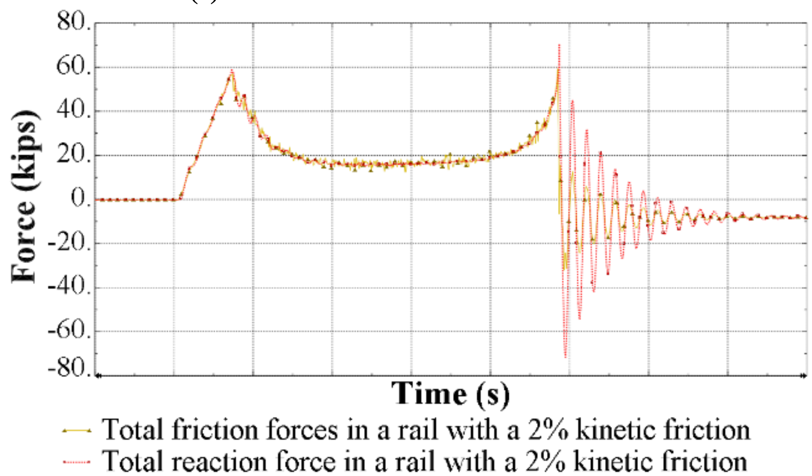
(b) Deflections due to weight

Figure 32. Temporary structure deflections in pressure regulated equal friction simulation

Transverse restraints were introduced to the second model, and differential kinetic friction of 3%was assumed between the rails. Sliding friction forces and temporary structure base reactions under differential friction were calculated and shown in Figure 33. Forces followed the same trend with equal friction, and 10% of the weight was observed at the onset of slide. Forces during the kinetic stage were 5% and 2% of the weight in the rails. Maximum amplitude of sliding forces during the dynamic stage was 1.8% and 4.5% of the weight in rails with 5% and 2% kinetic friction respectively. Lower kinetic friction results with larger dynamic forces. Static friction was defined equally in both cases. Forces were increased more rapidly during the transfer from the kinetic to static friction stage in the rail with a 2% coefficient of friction. This resulted in larger dynamic forces. Maximum amplitude in dynamic reaction forces followed the same trend with 7% and 10% of the weight in rails with 5% and 2% kinetic friction respectively.



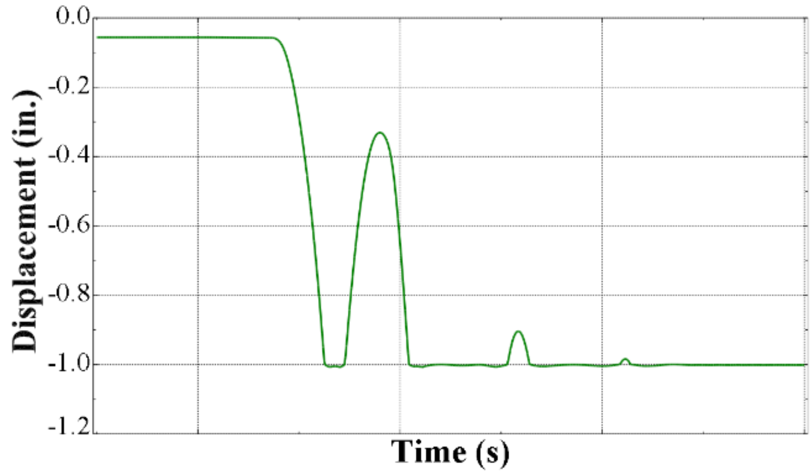
(a) Forces in rail with 5% kinetic friction



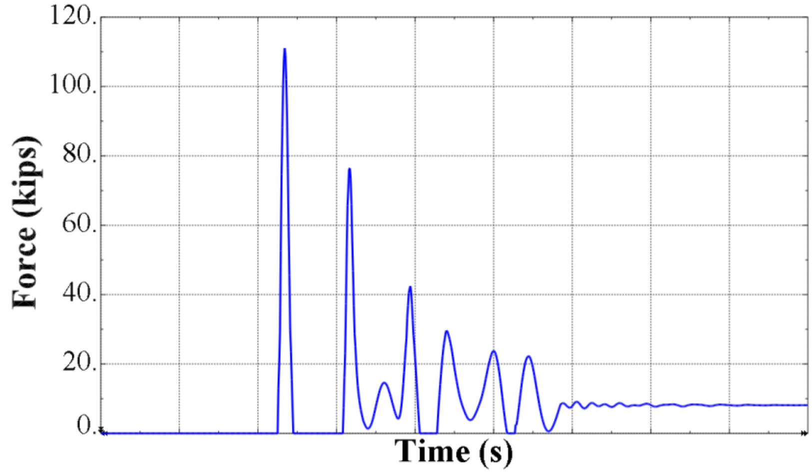
(b) Forces in rail with 2% kinetic friction

Figure 33. Forces developed in sliding direction in pressure regulated differential friction simulation

Differential friction forces caused the drifting of the superstructure. The superstructure drifted 1 in. towards the rail with 5% kinetic friction. Transverse movement of the bridge was limited to 1 in with restraints. Greater drift would have been observed if there were no restraints in the transverse direction. After the drift of the superstructure reached 1 in, the superstructure hit the restraint and bounced back until it was balanced and continued to slide with drifted orientation. The drift of the superstructure and forces developed on the transverse restraints are shown in Figure 34. The maximum force acting in transverse restraints was calculated as 15.4% of the total weight.



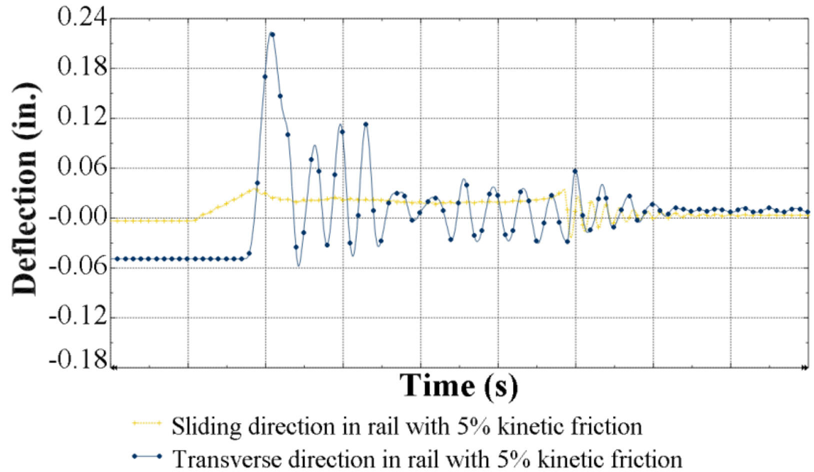
(a) Maximum transverse drift



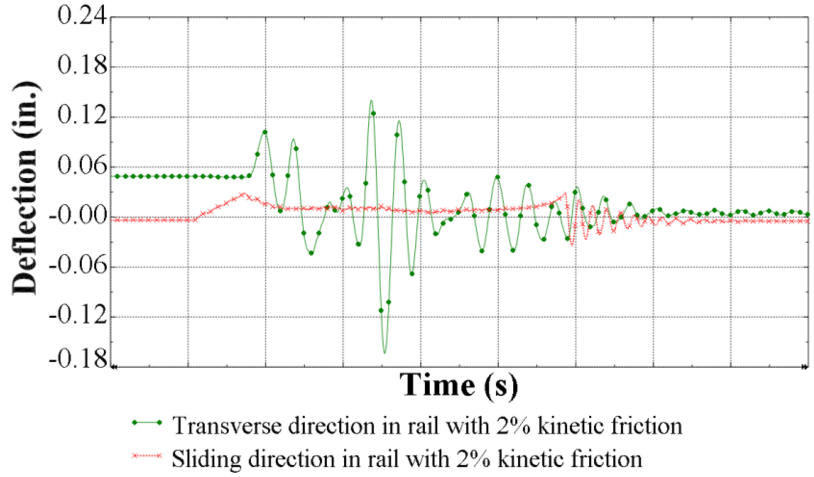
(b) Total reaction forces in transverse restraint

Figure 34. Drift and forces developed in transverse direction in pressure regulated differential friction simulation

Temporary structure deflections at the tip of the rails were calculated also for the differential friction model, as shown in Figure 35. Different deflections were observed in the sliding and transverse direction since sliding forces were different between rails. Deflections were calculated as equal in both rails in the gravity direction. Maximum deflection in gravity direction was the same as before and calculated as 0.035 in. Maximum deflections in sliding direction were calculated as 0.036 in. and 0.028 in. in rail with 5% and 2% kinetic friction respectively. Maximum deflections in the transverse direction were calculated at 0.222 in. and 0.162 in. in rail with 5% and 2% kinetic friction respectively. Differential friction introduced forces in the transverse direction and deflections increased significantly.



(a) Tip deflections in rail with 5% kinetic friction



(b) Tip deflections in rail with 2% kinetic friction

Figure 35. Extreme deflections of temporary structure in pressure regulated differential friction simulation

Servo Controlled System

In the simulations of the servo controlled actuating system, movement in a prescribed magnitude and direction was achieved. Sliding operation is independent from sliding resistance. Actuating forces are adjusted when there is a change in friction. As a result sliding direction is not affected by the change in resistance. An initial acceleration is developed to ramp up the velocity. After specific velocity is achieved, actuating forces can be balanced with the resistance, and the structure can be slid into place smoothly under constant velocity. Acceleration, velocity and displacement, which a superstructure undergoes in servo-controlled system analyses, are shown in Figure 36.

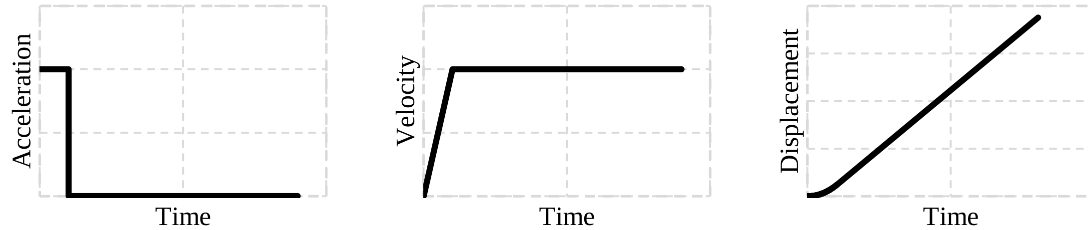


Figure 36. Variation of acceleration, velocity and displacement in servo controlled simulations

Servo controlled models were developed without any lateral restraint since drifting was not a concern. Equal and differential friction coefficients were defined between rails in separate analyses. Sliding friction forces developed in servo controlled simulations were calculated, and the typical response is shown in Figure 37. According to the results, friction forces are proportional with the frictional resistance. Sliding forces increase from zero to 10% of the weight at the onset of sliding. Sliding forces start to decrease with the decrease in resistance according to the specified decay rate of the coefficient of friction. Similar to a force regulated system, the friction force stabilizes after reaching the kinetic stage, which results in constant sliding friction force.

Sliding forces are transferred to the temporary structure, and reaction at the base of the temporary structure is calculated and shown in Figure 37. According to the results, forces are amplified due to inertia of temporary supports at the onset of sliding. This is due to initial increase in acceleration. Maximum friction force amplitude was 10% of the weight while it was 14.3% of the weight at the base of temporary structure.

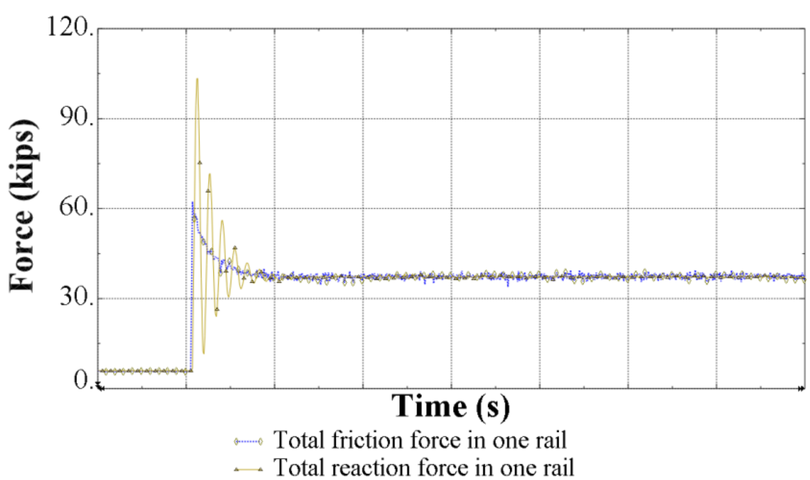
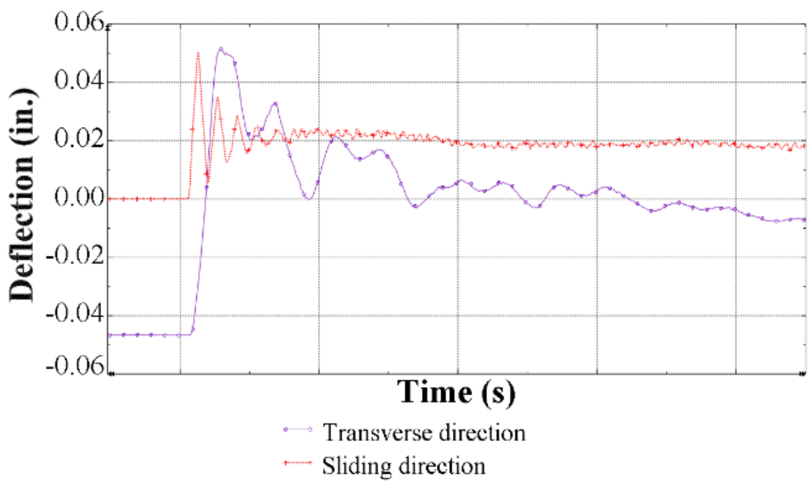
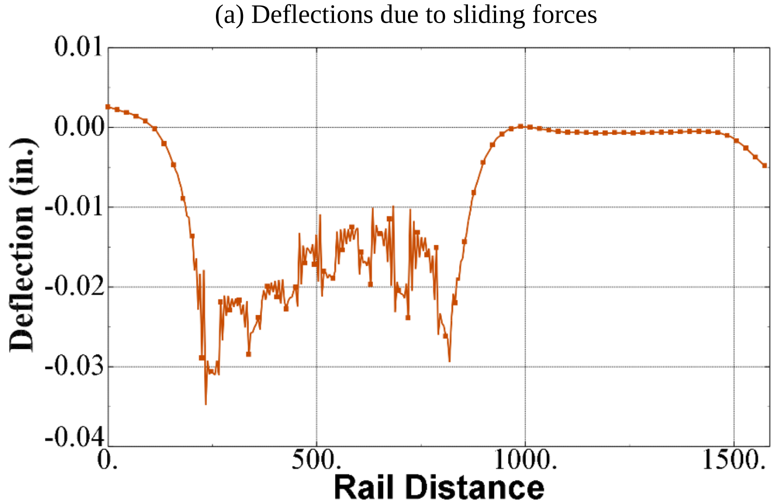


Figure 37. Forces developed in sliding direction in servo controlled equal friction simulation

Temporary structure deflections at the rail tips were calculated for the servo controlled system and shown in Figure 38a. In addition, deflections due to weight along the rails at the end of the pushing cycle in the direction of gravity were plotted in Figure 38b. Deflections were calculated as equal in both rails since there is no difference in friction. Maximum deflection in gravity was calculated as 0.035 in. Maximum deflections in sliding and transverse direction were calculated 0.051 in. Similar to pressure regulated equal friction simulation, the largest deflections are calculated in the transverse direction despite having zero forces in the transverse direction. Transverse deflections were developed due to gravity forces and low stiffness in that direction.



(a) Deflections due to sliding forces

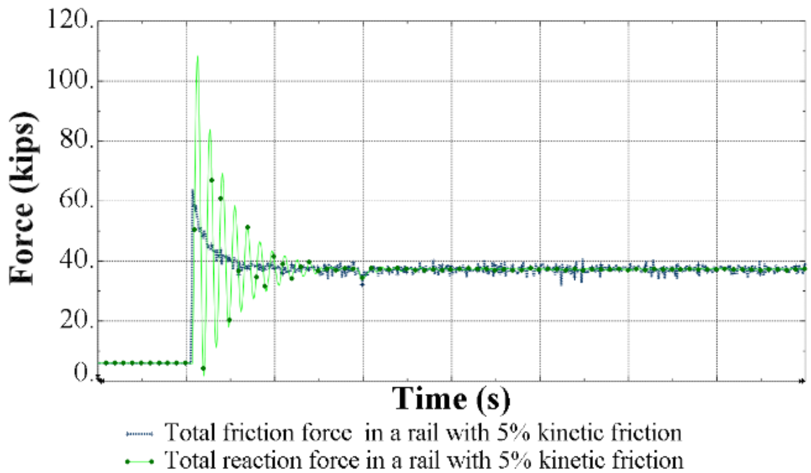


(b) Deflections due to weight

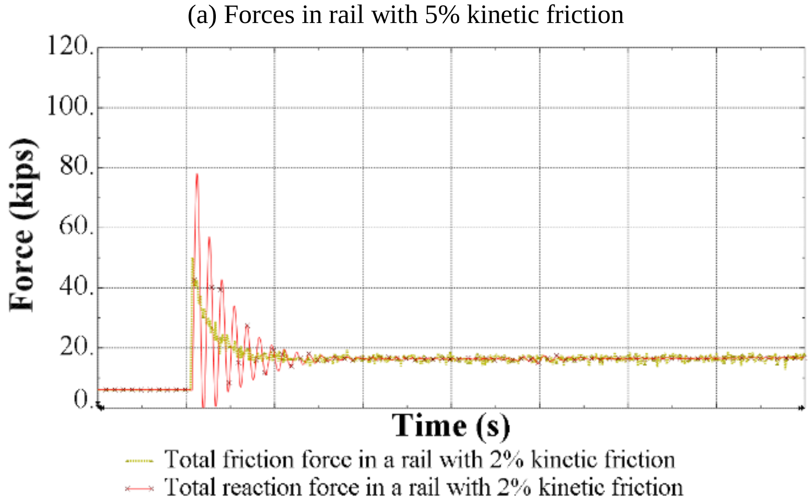
Figure 38. Temporary structure deflections in servo controlled equal friction simulation

As a second stage, kinetic friction was differentiated by 3% between the rails. Sliding friction forces and temporary structure base reactions under differential friction were calculated and shown in Figure 39. Sliding forces followed the same trend with equal

friction, and 10% of the weight was observed at the onset of slide. Sliding forces at the kinetic stage followed the kinetic friction defined in each rail. Similar dynamic amplifications were observed due to inertia forces of the temporary structure. Maximum reaction force amplitude was 15% and 11% of the weight at the base of the temporary structure in rails with 5% and 2% kinetic friction respectively.



(a) Forces in rail with 5% kinetic friction



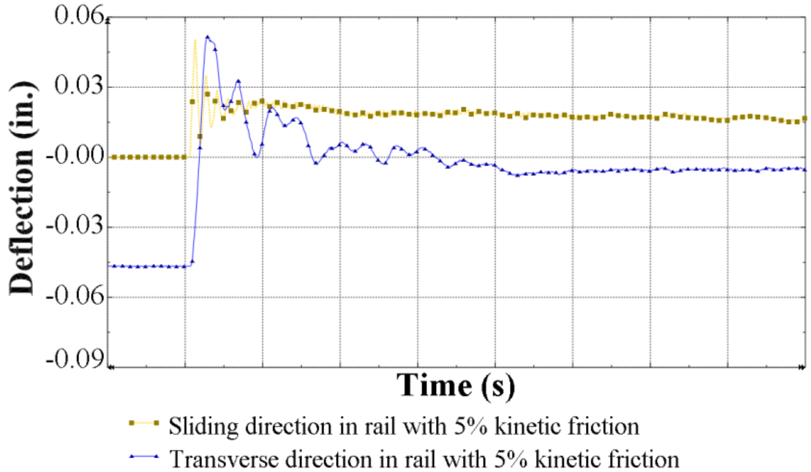
(b) Forces in rail with 2% kinetic friction

Figure 39. Forces developed in sliding direction in servo controlled differential friction simulation

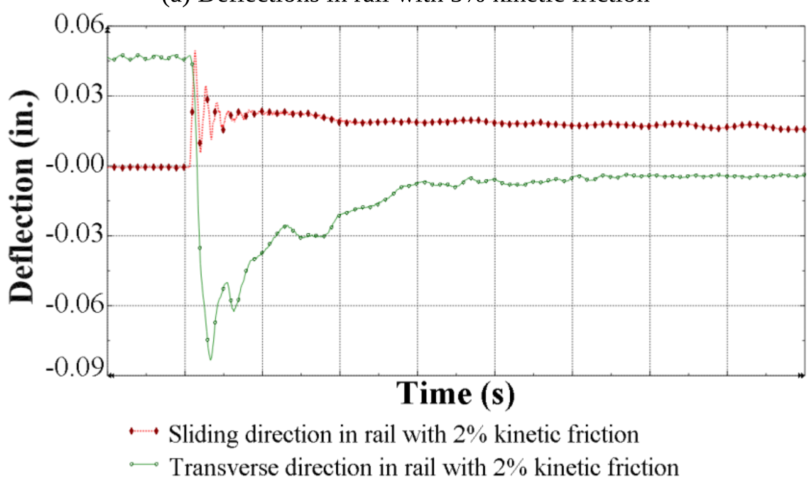
Differential friction forces were balanced with actuating forces to achieve the displacement targets in servo controlled simulations. As a result, no drifting was observed.

Even if differential friction forces do not generate drift, differential deflections are developed in temporary supports. More than 0.1 and 0.01 in. deflections are calculated in the sliding and transverse directions respectively. Histories are shown in Figure 40.

Temporary structure deflections at the rail tips were calculated also for the differential friction model and shown in Figure 40. Different deflections were observed in the sliding and transverse directions since sliding forces were different between rails. Deflections were calculated as equal in both the rail and gravity directions. Maximum deflection in gravity was the same as before and calculated as 0.035 in. Maximum deflections in sliding direction were calculated at 0.049 in. and 0.050 in. in rail with 5% and 2% kinetic friction respectively. Maximum deflections in the transverse direction were calculated at 0.052 in. and 0.083 in. in rail with 5% and 2% kinetic friction respectively. Deflections in the sliding direction were slightly larger than the pressure regulated system due to large dynamic forces at the onset of sliding. Deflections in transverse directions are less than pressure regulated systems since drifting was not developed.



(a) Deflections in rail with 5% kinetic friction

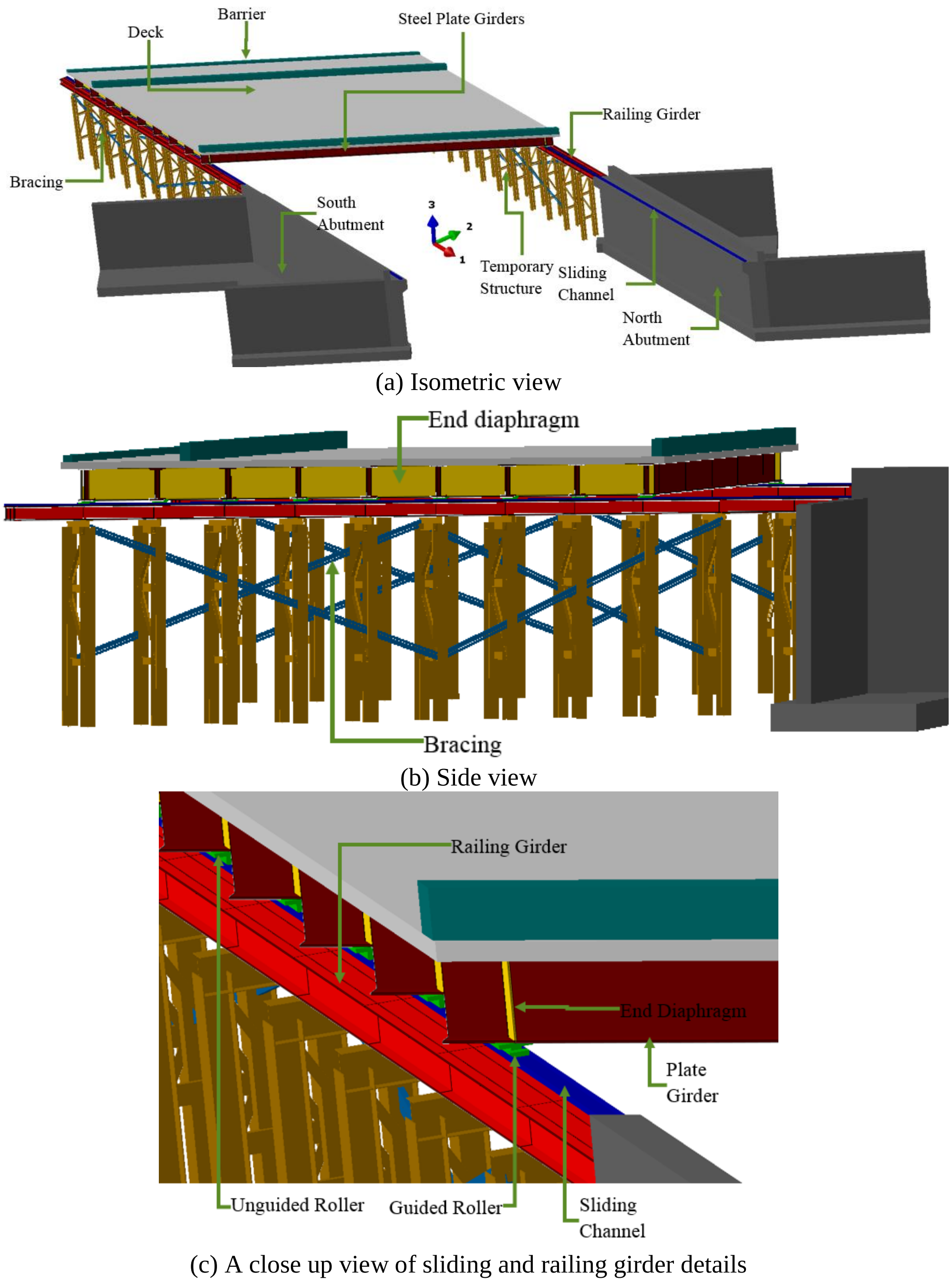


(b) Deflections in rail with 2% kinetic friction

Figure 40. Deflections of temporary structure in servo controlled differential friction simulation

Simulations of Lateral Slide with Pushing Type of Actuation and Inline Temporary Structure

The M-100 Bridge over CN Railroad was modelled to conduct simulations with a pushing type of actuation and an inline temporary structure. Simulations utilized pressure regulated actuation with a guided slide system. Effects of equal and differential friction were investigated. Geometry and components of the bridge are shown in Figure 41.



(c) A close up view of sliding and railing girder details

Figure 41. Geometry ad components of a FE Model with pushing type of actuation and inline temporary structure

Model geometry and material properties were based on bridge plans. Bridge deck, barriers, permanent abutments, rollers and a sliding channel were modeled with 3D solid elements. Steel plate girders, diaphragms and a railing girder were modeled with 2-D shell elements. The temporary structure was modeled with 1-D beam elements. The bridge superstructure was discretized with a coarse mesh since superstructure stresses are not the primary focus. The components of the lateral slide system were discretized by refined elements. The base of the piles in the temporary structure is modelled as fixed in all degrees of freedom. Contact interaction was defined between each roller and sliding channel with the contact pair feature of Abaqus. Frictionless contact surfaces are defined between side walls of the sliding channel and roller guides. As in the earlier model, Coulomb friction model was defined and assigned to contact pairs. Friction parameters are listed as static friction, kinetic friction and decay rate in the Coulomb model. Friction values and decay rate are defined from the frictional properties of Teflon pads. Friction coefficients of 3% to 5% static and 3% kinetic are adopted at interaction for rollers (Hilmann *n.d.*). The decay rate is defined as 1.5468 while decreasing the friction from 5% to 3% when the slip rate achieves 3 in/s which was the velocity defined for simulations. Coefficient of friction developed versus the slip rate, according to the Coulomb Friction Theory are shown in Figure 42.

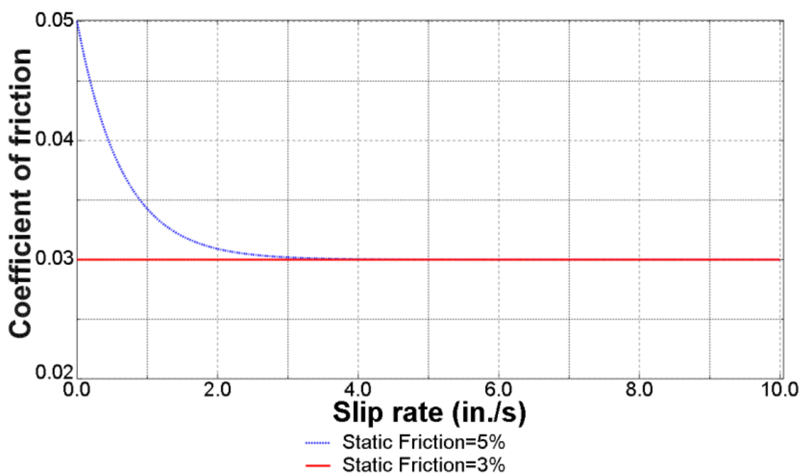
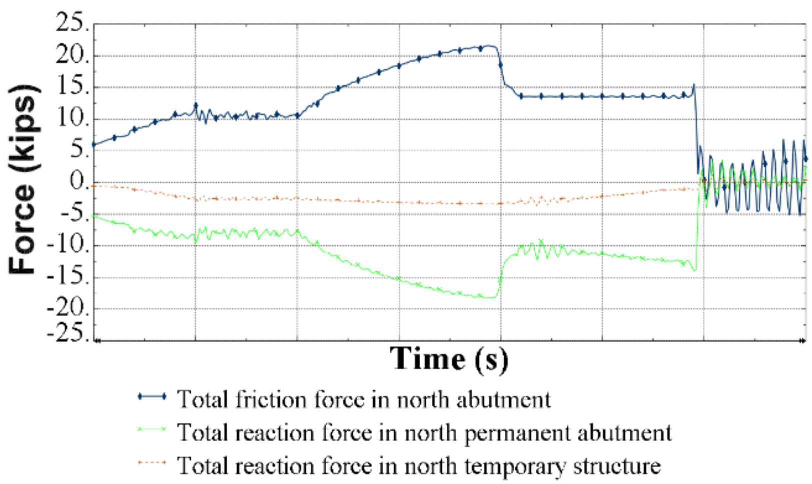


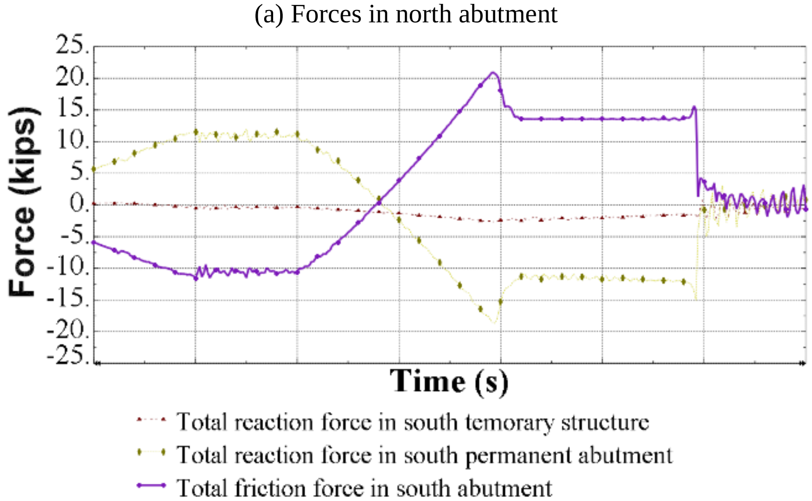
Figure 42. Coefficient of friction model used in US-131 simulations

The similar approach described in simulation of US 131 over 3 Mile Bridge is used to model the pressure-regulated system. Models were analyzed with equal and differential friction. Results of the equal friction model were explained first.

Sliding forces developed by contact and reaction forces at the base of the temporary structure and permanent abutment were calculated and shown in Figure 43. Initial forces were developed at the sliding surface as a result of the bridge skew. Sliding forces were resisted by the temporary structure and permanent abutment together. Forces in the sliding direction mostly transferred to the permanent abutment. Friction forces were equal to 5% of the weight. Reaction forces were calculated as 4% and 1% of the weight in the permanent abutment and temporary structure respectively. Inertia of the temporary supports increased dynamic forces developed at the base of temporary supports. Maximum friction force amplitude was 1.5% of the weight.



(a) Forces in north abutment

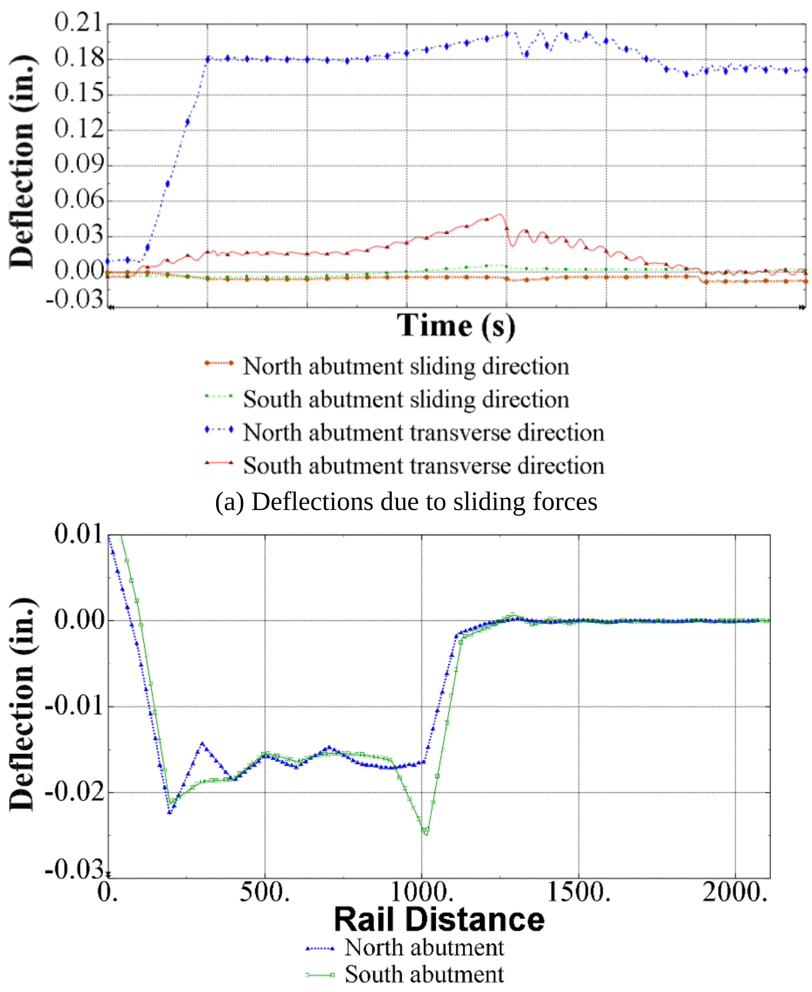


(b) Forces in south abutment

Figure 43. Forces developed in sliding direction in pressure regulated equal friction simulation

Temporary structure deflection at the tip of the rails were calculated and shown in Figure 44a. . In addition, deflections due to weight along the rails at the end of pushing cycle in the direction of gravity were plotted in Figure 44b. Deflections were calculated differential

in both rails because load distribution was not equal due to the skew. In addition, the stiffness of the temporary structure was also different. Maximum deflection in the gravity direction was calculated as 0.022 in. and 0.024 in. in the north and south abutment respectively. Maximum deflections in sliding direction were calculated at 0.007 in. and 0.006 in. in the north and south abutment respectively. Maximum deflections in the transverse direction were calculated at 0.048 in. and 0.205 in. in the north and south abutment respectively. Large transverse displacements were developed due to bridge skew.



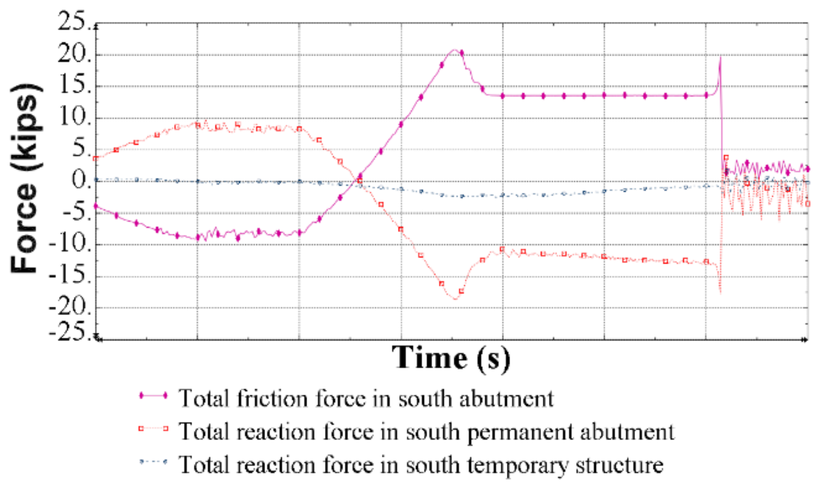
(a) Deflections due to sliding forces

(b) Deflections due to weight

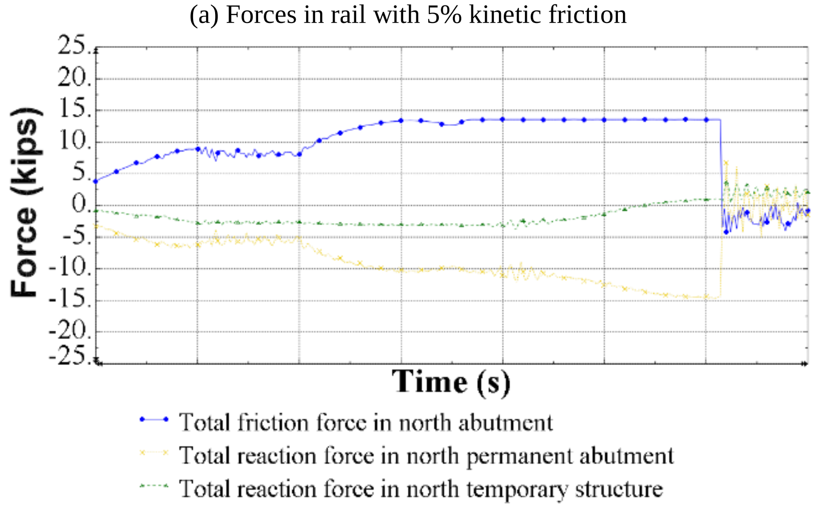
Figure 44. Deflections in pressure regulated equal friction simulation

Unequal friction model static friction was differentiated by 2% between the rails. Sliding friction forces, temporary structure and permanent abutment base reactions under differential friction were calculated and shown in Figure 45. Forces followed the same trend with equal friction, and 5% and 3% of the weight was observed at the onset of slide.

Forces during the kinetic stage were 3% of the weight in the rails. Reaction forces were calculated as 4% and 1% of the weight in the permanent abutment and temporary structure in the south abutment. Reaction forces were calculated as 2.4% and 0.6% of the weight in the permanent abutment and temporary structure in the north abutment. Inertia of the temporary supports increased dynamic forces developed at the base of temporary supports. However, forces had very low amplitude due to high stiffness of the temporary structure in both rails.



(a) Forces in rail with 5% kinetic friction



(b) Forces in rail with 3% static friction

Figure 45. Forces developed in sliding direction in pressure regulated differential friction simulation

Transverse forces developed in the system as a result of skew and differential friction. Drift was prevented by transverse restraints. Forces developed in the transverse restraints are shown in Figure 34. The maximum force acting on transverse restraints was calculated as 7% of the total weight.

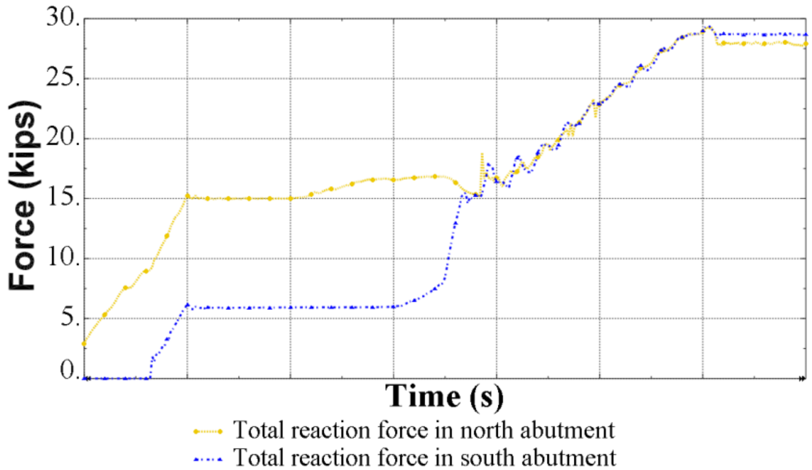
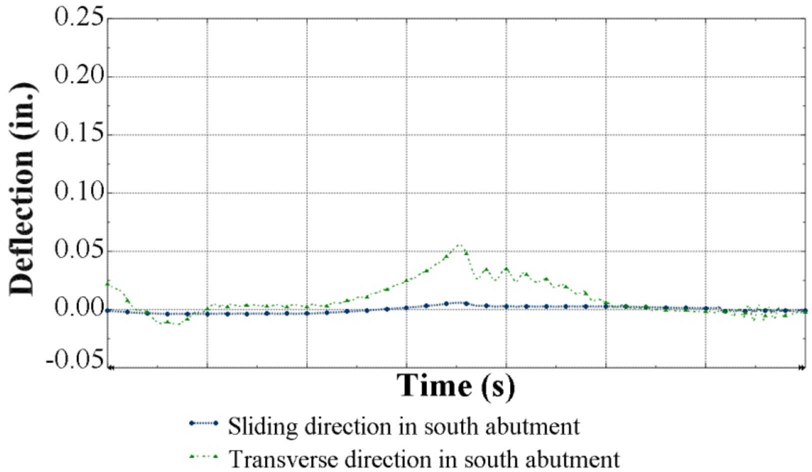
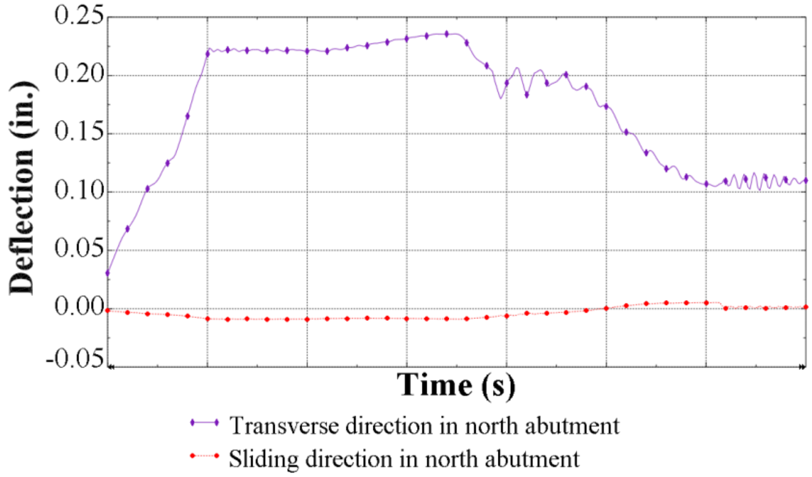


Figure 46. Forces developed in transverse direction in pressure regulated differential friction simulation

Temporary structure deflection at the tip of the rails were calculated also for the differential friction model and shown in Figure 47. Different deflections were observed in the sliding and transverse direction since sliding forces were different between rails. Deflections in the gravity direction were calculated similar to equal friction simulation. Maximum deflections in the sliding direction were calculated as 0.01 in. and 0.005 in. in rail with 5% and 3% static friction respectively. These deflections were minimized because most of the sliding forces are transferred to permanent abutments. Maximum deflections in the transverse direction were calculated as 0.055 in. and 0.235 in. in rail with 5% and 3% static friction respectively. Differential friction introduced forces in the transverse direction and deflections increased.



(a) Tip deflections in rail with 5% static friction



(b) Tip deflections in rail with 3% static friction

Figure 47. Tip deflections of temporary structure in pressure regulated differential friction simulation

Summary

Methods and procedures used in SIBC are identified and evaluated. Totally 28 completed SIBC projects are included in the evaluation of implementations. Distributions of span numbers, total span length and girder type of each project are plotted. SIBC is mostly preferred with single or two span bridges with a span length smaller than 300 ft. Precast concrete girder and steel I girder bridges are mostly preferred girder type in implementations.

Sliding systems, actuating systems and temporary structures are classified through implementations. Observations, advantages and challenges of utilized alternatives are identified from implementations.

Sliding systems are classified according to utilized transverse restraint type, sliding surface and sliding bearings. Alternatives for each classification are guided and unguided systems for transverse restraints, rollers and Teflon pads for sliding surface, and temporary and permanent bearings for sliding bearings.

Actuating systems are classified according to utilized actuating control mechanism, actuating method and actuating device. Alternatives for each classification are pressure regulated and servo controlled actuation for control mechanism, pulling and pushing for actuation method, and prestressing jack and hydraulic ram as actuation device.

Temporary structures are classified according to utilized temporary structure orientation and type of connection between temporary and permanent structures. Alternatives for each classification are inline and infront orientation, and continuous, semi-continuous and discontinuous type for connection.

Finite element simulations are developed with Abaqus/Explicit utilizing different alternatives observed in SIBC implementations. Differential and equal friction models are utilized in each simulation. Performed simulations are listed as;

1. Guided system with Teflon pads and pressure regulated control with pulling actuation, and infront temporary structure simulations

2. Unguided system with Teflon pads and pressure regulated control with pulling actuation, and infront temporary structure simulations

3. Unguided system with Teflon pads and servo controlled control with pulling actuation, and infront temporary structure simulations

4. Guided system with rollers and pressure regulated control with pushing actuation, and inline temporary structure simulations

Simulation results are useful to identify the time histories of forces possibly developed on sliding surface and at the base of temporary structures. Displacements of temporary structures are also calculated through simulations.

In the first simulation, static friction is kept at 10%, but the kinetic friction is differentiated between the rails as 2% and 5%. Maximum force amplitudes are calculated as 10% and 15.4% of the weight in sliding and transverse direction respectively. Maximum displacements of temporary structure are calculated as 0.036 and 0.222 in. in sliding and transverse direction respectively.

In the second simulation, static friction is kept at 10% and kinetic friction is kept constant at 5%. Maximum force amplitude is calculated as 10% of the weight in sliding direction. No forces are observed in transverse direction. Maximum displacements of temporary structure are calculated as 0.035 and 0.042 in. in sliding and transverse direction respectively.

In the third simulations, static friction is kept at 10% while kinetic friction is kept constant at 5% and differentiated between the rails as 2% and 5%. In constant friction simulation, maximum force amplitudes are calculated as 14.3% of the weight in sliding direction. No forces are observed in transverse direction. Maximum displacements of temporary structure are calculated as 0.035 and 0.051 in. in sliding and transverse direction respectively. In differential friction simulation, maximum force amplitude is calculated as 15 % of the weight in sliding direction. No forces are observed in transverse direction. Maximum displacements of temporary structure are calculated as 0.050 and 0.083 in in sliding and transverse direction respectively.

In the fourth simulations, static friction is kept constant at 5% and differentiated between rails as 5% and 3% while kinetic friction is kept constant at 3%. In constant friction simulation, maximum force amplitudes are calculated as 5% of the weight in sliding direction. No forces are observed in transverse direction. Maximum displacements of temporary structure are calculated as 0.007 and 0.205 in. in sliding and transverse direction respectively. In differential friction simulation, maximum force amplitudes are calculated as 5 % and 7% of the weight in sliding and transverse direction respectively. Maximum displacements of temporary structure are calculated as 0.01 and 0.235 in. in sliding and transverse direction respectively.

CHAPTER IV

STANDARDIZATION ALTERNATIVES

Chapter 3 evaluated SIBC methods and procedures through study of completed projects and analysis of FE simulation results. Different alternatives used in sliding systems, actuating systems and temporary sliding support structures, including their characteristics, are listed in Chapter 3. The previous chapter also presented standardized system selection charts developed according to results of the studies and analysis. These flow charts are useful in the selection process of complete lateral slide systems, as shown below. The charts displayed below also include decision processes followed by convenient alternative selections. Structural concerns are questioned in decision processes, and alternatives are suggested as a solution to those questions. Each alternative required several design considerations in order to function properly which is explained in this section.

Selection charts create a path, including several decision processes and alternative selections, to design a complete lateral bridge slide system. In total, 54 different, complete lateral bridge slide systems are possible. The first chart starts with a decision concerning the transverse restraint type to identify whether transverse constraints are desired (Figure 48). The process continues with determination of sliding and actuating system alternatives through several decision steps (Figure 49 and Figure 50). The process concludes with a temporary structure decision process and a selection of alternatives (Figure 51). A reference number is given to all boxes in the charts. Those numbers refer to related decision processes and alternatives in Table 4 and Table 5.

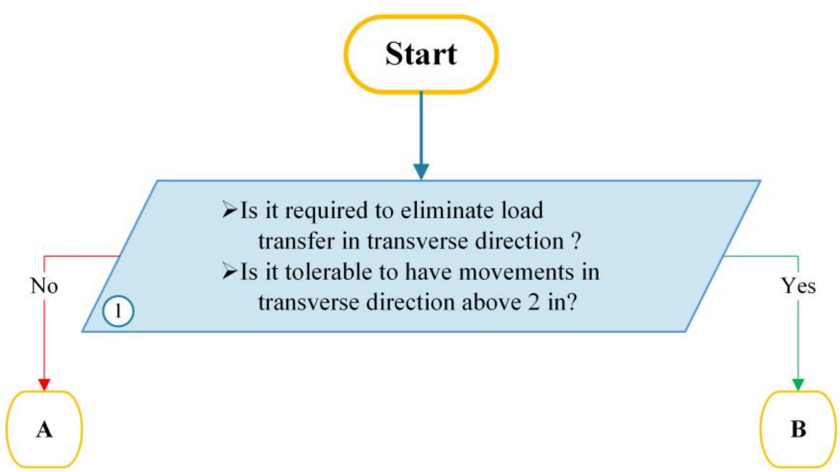


Figure 48. Step 1: Selection of transverse restraint type

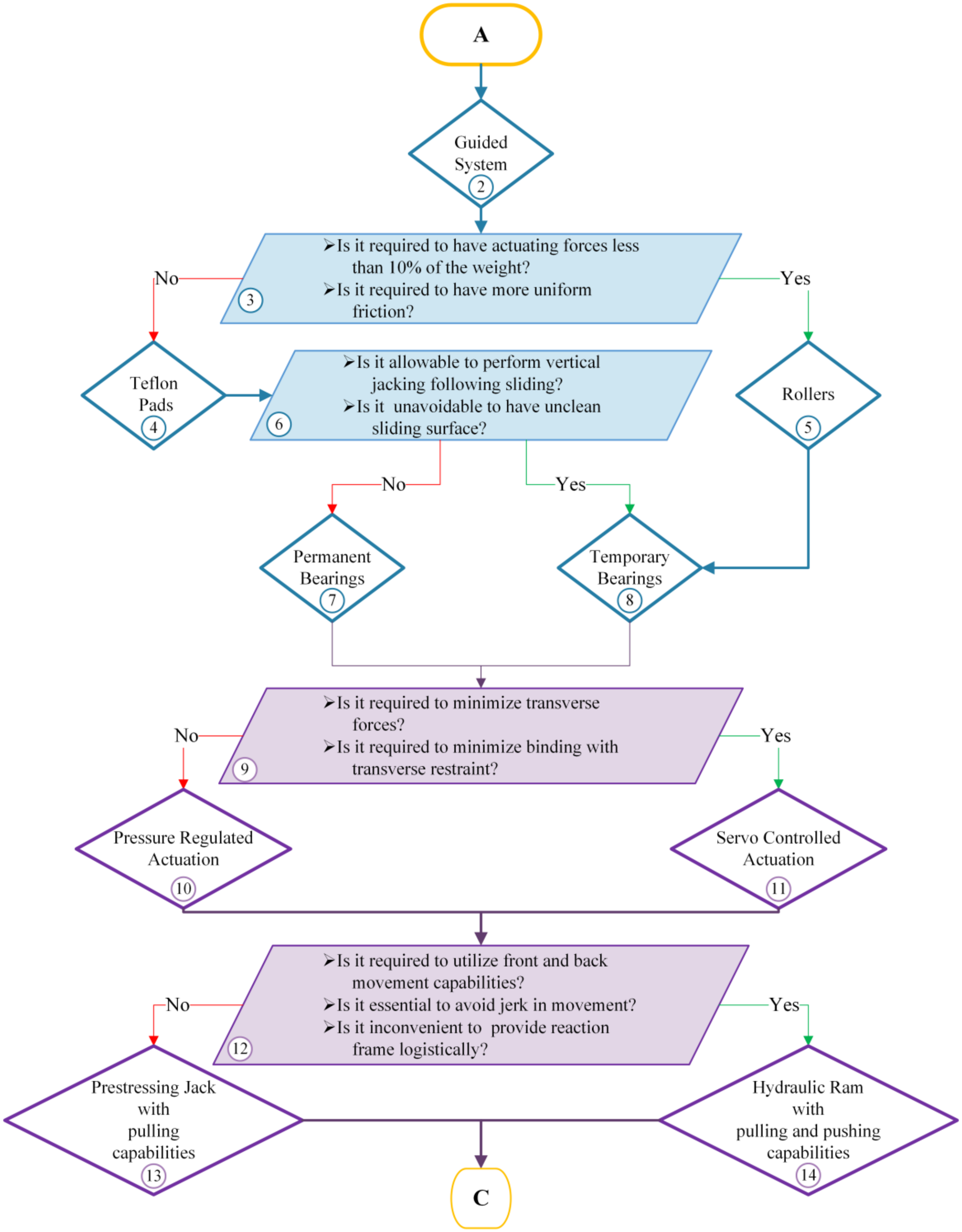


Figure 49. Step 2: Selection of sliding and actuating systems

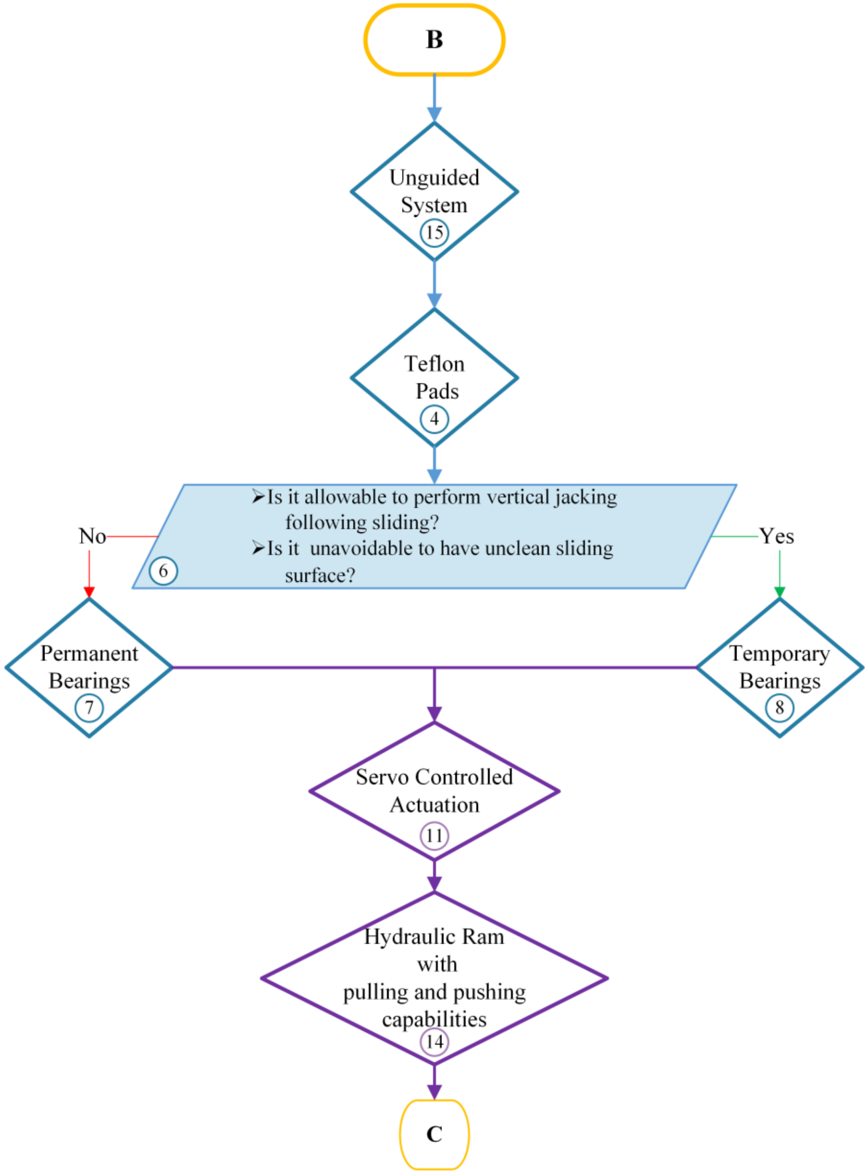


Figure 50. Step 2: Selection of sliding and actuating systems

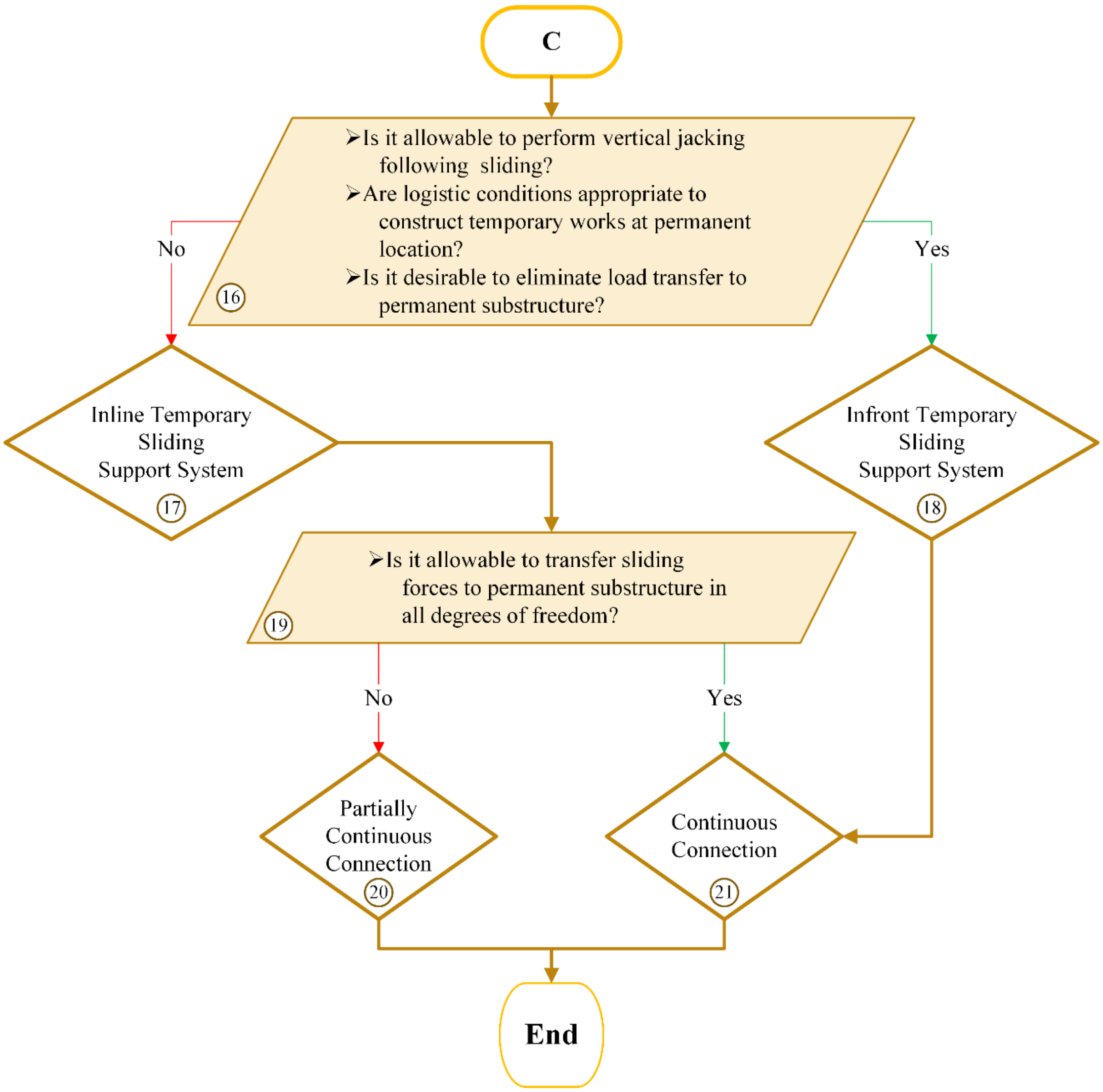


Figure 51. Step 3: Selection of temporary sliding support structure

Table 4, below, explains the decision processes above and describes possible alternatives.

Table 4. Decision Reference Table

Decision Reference Number	Related Component	Definitions
1	Sliding System	• Decision of transverse restraint system. Selection defines allowable tolerances in transverse direction and load transfer to support structure. • Alternatives are guided and unguided systems. A guided system restrains transverse movements but transfers transverse forces to a support structure while an unguided system releases transfer movements but eliminates transverse force transfers to a support structure.
3	Sliding System	• Decision of sliding surface. Selection defines magnitude of actuating force and uniformity of sliding • Alternatives are Teflon pads and rollers. Coefficient of friction is between 5% and 20% for Teflon pads while it is between 2% to 5% in rollers. Static and kinetic friction coefficient difference is around 5% in Teflon pads while it can be neglected in rollers.
6	Sliding System	• Decision of bearing type for sliding. Selection defines required operation during and after sliding. • Alternatives are temporary and permanent bearings. Temporary bearings require vertical jacking following sliding operation and an unclean sliding surface is more tolerable. Permanent bearings eliminate need of vertical jacking; however, it requires a cleaner and smoother sliding surface.
9	Actuating System	• Decision of actuating system. Selection defines actuation control mechanism. • Alternatives are pressure regulated and servo controlled actuation. Pressure regulated actuation includes control of pressure in a hydraulic system. Servo controlled actuation includes instantaneous displacement monitoring with automated and synchronized pressure regulation.
12	Actuating System	• Decision of actuating type and mechanism. Selection defines direction and utilized mechanism of actuating forces. • Alternatives are hydraulic ram with pulling, pushing capabilities and prestressing jack with pulling capabilities.
16	Temporary Sliding Support Structure	• Decision of support structure orientation. • Selection defines if the temporary sliding support structure is in line with permanent supports or in front of the permanent support.
19	Temporary Sliding Support Structure	• Decision defines the connection between in line temporary support and permanent structure. • Alternatives are continuous and partially continuous connection. Load transfer is allowed in all degrees of freedom in a continuous connection while load transfer is released only with some degree of freedom in a partially continuous connection.

General design requirements have to be provided regardless of the lateral bridge slide system selected. The design requirements are listed as follows:

- Lateral bridge slide systems' design calculations and drawings should be provided in detail with bridge plans.

- Moving load analysis should be performed to identify dynamic effects of sliding forces.
- A deflection check should be performed for a temporary structure.
- Slide monitoring should be planned and applied carefully during the slide.
- Potential challenges should be identified according to uncertainties explained for each system, and contingency plans should be developed accordingly.

In addition to general requirements, each alternative has various considerations to be fulfilled when utilized. Table 5 summarizes respective considerations for each alternative.

Table 5. Alternative Specific Considerations

Alternative Reference Number	Specific Considerations
2	• Transverse forces up to 15% of the weight should be considered as a result of guided system selection. • Final lateral alignment should be avoided because of the disability of transverse movements in guided systems.
4	• Thickness of pads should be checked. • Reuse of the pads should be avoided. • Lubricants should be used with dimpled pads. • Experiments should be performed to identify the friction coefficient. Friction coefficients are different in each project since bearing pressure and sliding velocities are project specific. • A test slide should be performed to verify the experimental results.
5	• Undesirably low friction should be considered since it is possible with rollers. • High point loads developed under rollers should be considered. • A test slide should be perform to verify the estimated friction.
7	• Excessive friction forces should be avoided so as not to damage to the permanent bearings.
8	• Stresses developed as a result of vertical jacking should be considered.
10	• Maximum allowable drifting should be limited to 2 in. • Pressure limits should be defined for emergency stops
11	• Pressure limits should be synchronized with displacement sensors.
13	• Jerk in movement should be considered. • An emergency brake cable should be provided in uphill slides.
14	• Diaphragm design should be checked under forces applied by ram. • Clevis or swivel connection should be utilized between stroke and end diaphragm. • Tolerances should be provided in the connection to the railing girder. • Capacity and stroke length should be selected appropriately. • Self-retracting rams should be considered.
15	• Misalignments developed during slides should be observed carefully.
17	• Possible eccentric load transfers to the permanent substructure should be evaluated.
18	• Load transfer to the permanent substructure should be considered.

CHAPTER V

SUMMARY, CONCLUSION AND FUTURE RESEARCH

Summary and Conclusion

Slide in bridge construction (SIBC) requires additional activities compared to conventional construction. These additional activities are related to the lateral bridge slide operation to move the bridge to its final position following construction. The critical components of the lateral bridge slide are the sliding system, actuating system and temporary sliding support structure. The goal of this study is to develop standard procedures for lateral bridge slide operation. The specific tasks were (a) evaluating SIBC activities nationally in the slide perspective, and (b) performing rigorous analysis of complete lateral bridge slide systems through finite element simulations.

In the first task, a total of 28 SIBC projects were reviewed and different slide systems, actuating systems, temporary sliding support structures, accomplishments, and challenges in utilized components were identified. Compatible systems, required decisions, and design considerations of alternative options are used in the development of standard procedures for lateral bridge slide systems.

In the second task, FE simulations were conducted incorporating various parameters for slide systems, actuating systems and temporary structure. 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 simulations included: unguided and guided sliding systems with Teflon pads, pressure regulated and servo controlled actuation systems with a pulling method, and an infront temporary sliding support structure. The second model described the lateral bridge slide of the M-100 Bridge over CN Railroad. 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 projects' outcomes.

Following conclusions are derived according to outcomes of SIBC implementations and FE simulations:

- Each sliding systems should include a transverse restraint, sliding surface and sliding bearing alternatives.

- Guided and unguided systems are the two alternatives as transverse restraint type. Guided systems restraints movements in transverse direction with providing constraints. Transverse forces up to 15% of the weight should be taken into consideration when guided systems are utilized. Tolerances between the transverse restraint and sliding bearings should be less than 2 in. to classify sliding system as guided. Restraints are not provided in unguided systems. However transverse drift of a system should be limited to 2 in. and monitored.

- Teflon Pads and rollers are the two alternatives to utilize as sliding surface. Teflon pads should be dimpled. Lubricant use should be minimized. Teflon pads should be designed as a bridge bearing and should be reinforced with steel according to AASHTO specifications. Future studies are required to determine minimum Teflon pad thickness and maximum allowable pad deformations. Friction is a function of bearing pressure, sliding velocity and Teflon composition. Therefore friction tests should be performed to identify the coefficient of friction of the specific Pads which will be used in the slide. Design bearing pressure and sliding velocity should be included in the test. In addition, slide tests should be performed to verify the coefficient of friction determined in the tests are valid for slide. Rollers provide more stable friction. Friction coefficients are already standardized by roller manufacturers. Suitable rollers should be selected for design bearing pressure according to manufacturers' product catalogs. Large point loads are developed under rollers and friction can be very low compared to Teflon pads. Test slide is required again in order to identify the exact friction under field conditions.

- Temporary and permanent bearings are the two alternatives to utilize as a sliding bearing. If temporary bearings are utilized, number of temporary bearings should be minimized to achieve large bearing pressures to decrease the coefficient of

friction. Bearing pressure under temporary bearings with Teflon pads should be between 500 and 2000 psi in order to have 5% to 10% friction coefficient. It is not necessary to provide bearings under each girder. Bearing pressure should be determined according available capacity of rollers when they are utilized. Permanent bearings should be selected only if vertical jacking is not desired and when clean sliding path is not guaranteed.

- Each actuating system should include actuation control mechanism, actuation method and actuation device.

- Pressure regulated and servo controlled actuations are the two alternatives to utilize as an actuation control mechanism. Servo controlled actuation is recommended to have a better control during the slide to minimize drifting and binding challenges. Pressure regulated actuation shall only be utilized with guided system where transverse movements are restrained.

- Pulling and pushing methods are the two alternatives to utilize as an actuation method. Both pulling and pushing capabilities should be provided with unguided systems to increase sliding control in case drifting occurs. Only one method can be sufficient with guided systems however it is recommended to provide pushing and pulling capabilities in the contingency plans of guided systems.

- Hydraulic rams and prestressing jacks are the two alternatives to utilize as an actuation device. Hydraulic rams should be double acting, that is, have the capability to pull and push capabilities. Clevis or swivel connection should be provided between ram and superstructure. It is strongly recommended to utilize self-retracting rams to eliminate challenges observed in ram and temporary structure connections. Prestressing jacks have only one directional movement since they are used with tension cables/rods. Jerk in movement is inevitable because of the prestressing losses and cable flexibility. Hydraulic capacity of both rams and jacks should be determined according to weight of the bridge, coefficient of friction and sliding velocity. Stroke length should be greater than 10 in. to minimize device

retracting durations. Stroke lengths larger than 30 in. are not recommended in order to have sufficient stops to control drifting and binding of the moving bridge.

- Inline and infront orientation are the two alternatives to utilize as a temporary structure. Logistic conditions should be investigated to determine the appropriate orientation alternative. Temporary structure deformations should be limited in sliding, gravity and transverse direction. Large deflections affect the contact in sliding surfaces and bearing pressure which can dramatically change friction force developing among bearings or rollers. As a result drifting and binding may occur and sliding performance is affected. Temporary structure stiffness should be sufficient enough to limit deflections to less than 0.05 in. in sliding, transverse, and gravity direction. Sufficient stiffness is generally provided in sliding and gravity direction and deflections are kept small. However, transverse stiffness of temporary structure is not considered as critical generally, since forces are not expected to develop in transverse direction. However evaluation showed that differential friction is inevitable and forces in transverse direction are developed with differential friction. Simulations showed that 0.2 in. deflections are developed in transverse direction while deflections in sliding and gravity directions are around .0.03 in. Transverse stiffness of temporary structure should be increased to decrease transverse deflections. Deflection dependent friction changes can be minimized to decrease the possible binding and drifting challenges. In addition transverse stiffness is more significant in skew bridges since internal forces developed due to skew deflects temporary structure without any differential friction Temporary structure deflections should be limited in all directions to increase sliding performance.

- Continuous and semi-continuous connections are the two alternatives to utilize between sliding supports at temporary and permanent locations. Continuous connection is recommended to achieve continuous sliding path. Simulations showed that up to 80% of the sliding forces are transferred to permanent structure through connection. Connection and permanent structure should be designed properly to handle developed forces. If there is a concern for load transfer in certain

degree of freedom semi continuous connection can be utilized. However continuity of sliding path through the connection should be maintained in order not to have challenges at the connection during the slide.

- In addition to system specific conclusions, detailed calculations and drawings should be provided in the plans. Developing and implementing detailed monitoring and contingency plans for sliding procedure are essential to improve sliding performance regardless of the type of the selected sliding system, actuating system and temporary structure.

Future Research

This study was performed to develop standard procedures for lateral bridge slides. Due to a lack of quantitative data concerning such a new process, mostly qualitative data was used to accomplish this study. Qualitative parameters are unknowns despite having approximate predictions. This study finds FE simulations to be resource in demonstrating the sources of challenges. However, in order to take the next step, lateral bridge slides should be instrumented and monitored. Actuating forces, sliding displacements, velocities or accelerations and deflections of temporary structures should be recorded. Recording actuation force histories can be accomplished by attaching load cells on the piston of the actuation device. Displacement, velocity sensors or accelerometers can be utilized to record movements. The magnitude of required tolerances and capabilities for each design alternative can be identified with quantitative data collected from lateral bridge slides. In addition, explicit FE simulations can be enhanced with defining better actuation and friction models based on the collected data. Different sliding system, actuating system, temporary structure, superstructure type, and geometry configurations should be analyzed to calculate the magnitude of forces and deflections. Parametric simulations can be developed to identify effects of different skew angle, Teflon pad thickness, temporary structure stiffness, and temporary bearing numbers. Slide monitoring and simulations are essential to improve design requirements for future applications.

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APPENDIX

Abbreviations used in the text explained in this section.

ABC	: Accelerated Bridge Construction
AASHTO	: American Association of State Highway and Transportation Officials
CDOT	: Colorado Department of Transportation
CN	: Canadian National
DOT	: Department of Transportation
FE	: Finite Element
FHWA	: Federal Highway Administration
Iowa DOT	: Iowa Department of Transportation
MDOT	: Michigan Department of Transportation
ODOT	: Oregon Department of Transportation
PTFE	: Polytetrafluoroethylene
SASHTO	: Southeastern Association of State Highway and Transportation Officials
SHRP	: Strategic Highway Research Program
SIBC	: Slide-In Bridge Construction
UDOT	: Utah Department of Transportation
US	: United States