FHWA LTBP Workshop to Identify Bridge Substructure Performance Issues: March 4–6, 2010, in Orlando, FL

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Research, Development, and Technology
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FOREWORD

This report is a product of the Long-Term Bridge Performance (LTBP) program. The program was authorized under the 2005 *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users* to identify, collect, and analyze research-quality data that will provide a better understanding of bridge performance and lead to improvements thereof.[1] This report presents an overview of the "Federal Highway Administration Workshop to Identify Bridge Substructure Performance Issues," held in Orlando, FL, from March 4 to 6, 2010. The purpose of the workshop was to consider overall bridge performance and identify geotechnical performance metrics that may correspond to good and poor performance. This report describes the results of the workshop and presents them in the larger perspective of designing and implementing the LTBP program. This document will be of interest to engineers who research, design, construct, inspect, maintain, and manage bridges as well as to decisionmakers at all levels of management of public highway agencies.

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Director, Office of Infrastructure
Research and Development

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16. Abstract

The Long-Term Bridge Performance (LTBP) program was created to identify, collect, and analyze research-quality data on the most critical aspects of bridge performance. To complete a thorough investigation of bridge performance issues, the Federal Highway Administration (FHWA) sponsored the "FHWA Workshop to Identify Bridge Substructure Performance Issues" in Orlando, FL, from March 4 to 6, 2010. The workshop included participants from FHWA, State transportation departments, academia, industry, and consultants. The workshop had three focal points: (1) identify bridge performance issues impacted by geotechnical factors, (2) identify data needs and data gaps related to the geotechnical performance issues, and (3) identify tools, technology development, and monitoring to address the data needs and data gaps. This report describes the results and recommendations of the workshop and presents them in the larger perspective of designing and implementing the LTBP program.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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INTRODUCTION

This report presents an overview of the "Federal Highway Administration (FHWA) Workshop to Identify Bridge Substructure Performance Issues" held in Orlando, FL, from March 4 to 6, 2010, and it documents the results and conclusions of that workshop. The workshop consisted of 2.5 days of meetings to consider overall bridge performance and identify geotechnical performance metrics that may correspond to good and poor performance. The first 2 days consisted of meetings with FHWA personnel, the Long-Term Bridge Performance (LTBP) program research team, and 34 invited attendees representing State highway agencies, FHWA headquarters, Federal aid, Federal lands, and research; academia; and consultants. The final half-day session consisted of discussions among FHWA personnel and the LTBP research team to evaluate the results of the workshop and determine what follow-up activities were necessary to capitalize on the workshop results. This document is intended to record the results of the workshop and frame them in the larger perspective of designing and implementing the LTBP program.

OBJECTIVE OF THE LTBP PROGRAM

The objective of the LTBP program is to compile a comprehensive database of high-quality quantitative data to better understand the critical factors that impact the performance of bridge elements and the bridge as a whole. These data are collected by studying representative samples of bridges nationwide and are supplemented with data from other sources.

The transportation system in the United States depends on about 500,000 bridges for grade separations, interchange configurations, and crossings over natural barriers, such as rivers. The operation and functionality of the highway network depends on the performance of these structures. Many aspects of bridge performance are not well understood, and several factors contribute to that lack of understanding. Although bridges in the United States share significant similarities such as structure type, basic material properties, and design details, many characteristics vary significantly from bridge to bridge. Other barriers to understanding bridge performance include the following:

- Multiple variable causative factors impacting performance.
- Limited understanding of some cause-and-effect relationships.
- Limited availability of suitable critical data.
- Differing bridge policies and practices among owners.
- Gradual improvements to design and construction practices.
- Introduction of new and improved bridge materials.

FHWA has initiated the LTBP program as a 20-year research effort that is strategic in nature and has both specific short- and long-term goals. Under the LTBP program, several structure types that are common in the bridge infrastructure will be studied. Significant variables include material characteristics, age, traffic volumes, truck loads, climatic conditions, and other factors that impact bridge performance. As a part of this program, the most critical aspects of bridge performance will be identified, knowledge gaps related to these performance issues will be addressed, and high-quality quantitative performance data will be collected. The long-term data collected under the LTBP program will make it possible to develop reliable deterioration and performance models based on the cause-and-effect relationships determined by analyzing the LTBP data. Many benefits will arise from the results of the LTBP program. One of the most significant will be improvements in the management of bridge programs at the Federal, State, and local levels. Transportation agencies will be able to target scarce resources at the bridge deficiencies that affect performance and thereby provide improved service to the traveling public.

LTBP researchers will conduct detailed periodic inspections, monitoring, and evaluations of the population of bridges representing the national bridge inventory by using finite element modeling, instrumentation to monitor bridge behavior, physical testing of material characteristics, nondestructive evaluation (NDE) techniques, and detailed visual inspections. NDE techniques include ground penetrating radar to detect flaws and corrosion inside structures and sensor technologies that monitor traffic loading, cracks due to fatigue and corrosion, overloads, environmental conditions, etc. Researchers will conduct recurrent, periodic evaluations for selected bridges throughout the life of the program and may perform forensic autopsies of decommissioned bridges to learn more about their capacities, reliabilities, and failure modes.

The LTBP program, while similar to the FHWA Long-Term Pavement Performance program, is an effort that is unprecedented in scope and scale in the area of long-term bridge research. A large investment of public dollars is being made in the program, which must produce results to both justify the expenditure and meet the expectations of the various stakeholders and partners in academia, transportation agencies, and industry. It is of paramount importance that the FHWA program managers understand the needs and expectations of these entities and gain the benefit of their collective experience and knowledge in designing and implementing the LTBP program. In order to ensure these advantages, FHWA reached out to its stakeholders to obtain input on the design of the program.

With the help of the National Science Foundation, FHWA sponsored a workshop, "Future Directions for Long-Term Bridge Performance Monitoring, Assessment, and Management," held in Las Vegas, NV, on January 9 and 10, 2007. Workshop participants were invited by FHWA to ensure an effective mix of backgrounds and perspectives. Participants came from State transportation departments, domestic and international universities, industry, and consultants, as well as from FHWA. The core of the workshop included deliberations by three carefully chosen breakout groups on three key elements of the program: (1) data to be collected, (2) short- and long-term deliverables, and (3) bridge sampling for selection and monitoring. The results of this workshop were documented in an unpublished report that became the foundation for the development of the LTBP program.

As part of the development of the program, the LTBP research team conducted focus group meetings with the bridge office personnel of 15 State transportation departments. The purpose of these meetings was to capture the experience and knowledge of bridge experts regarding the following topics:

- The most pervasive bridge performance issues they face.
- The data they currently use to understand and act on performance issues.
- The additional data and knowledge that would enable them to better understand the issues and develop more effective and economical solutions.

The conclusions from the focus group meetings will be published in a report documenting data needs for the LTBP program. Issues identified during these meetings included the following structural foundation elements or geotechnical factors:

- Performance of bare/coated concrete superstructures and substructures.
- Methods to measure scour that are direct, reliable, and timely.
- Performance of scour countermeasures.
- Performance of structure foundation types.
- Identification and performance of unknown foundation types.
- Performance of bridge bearings (all types).
- Performance of jointless structures (integral, semi-integral, and continuous for live load).

To further evaluate these issues and refine the issues for which LTBP program studies would be effective, FHWA sponsored the "FHWA Workshop to Identify Bridge Substructure Performance Issues," held in Orlando, FL, from March 4 to 6, 2010. The workshop format was similar to the workshop held in Las Vegas, NV. Attendance was by invitation so that an effective mix of backgrounds and perspectives would be represented. Workshop participants came from State transportation departments, domestic universities, industry, and consultants, as well as from FHWA. The core of the workshop included deliberations in three carefully chosen breakout groups on three key elements of the program: (1) bridge performance issues (impacted by geotechnical factors), (2) data needs and gaps (related to the issues identified), and (3) tools, technology development, and monitoring (related to the data gaps).

In the following sections, the progress of the workshop is documented in chronological order according to the agenda, which is included in appendix A. This format documents developments as the workshop attendees discussed the various topics in the breakout sessions. The session summaries were prepared utilizing notes taken by session scribes. The participants received little information in advance of the workshop so that they would come to the workshop with open minds. Two background handouts were provided to participants at the start of the meeting. The first handout provided general information and is included in appendix B. This handout detailed the objective of the workshop, expected outcomes, background, breakout sessions, and invited attendees. This information was also reviewed by various speakers in the plenary session. A second handout, "Identification of Bridge Performance Study Topics," included in appendix C, provides an overview of suggested LTBP study topics from previous stakeholder meetings.

SUMMARY OF THE PLENARY SESSION: LTBP PROGRAM OVERVIEW

INTRODUCTION TO THE PLENARY SESSION

The workshop began with a series of presentations that were designed to focus the efforts of the participants on helping FHWA formulate the future direction and activities of the LTBP program in the geotechnical arena. In more specific terms, the participants were asked to identify and define the key issues and actions related to (1) bridge performance issues related to substructure and foundations, (2) data needs and gaps related to the key performance issues, and (3) tools, technology development, and monitoring necessary to collect critical geotechnical performance data for the LTBP program.

The plenary session concluded with a presentation that highlighted topics of the three breakout sessions. The participants were divided into three groups to brainstorm and discuss the three main topics of the workshop. The following topics were discussed in the order shown because the results of each breakout session fed into the succeeding session:

- **Bridge performance issues**—Workgroups were directed to discuss key performance issues related to substructure and foundations. They were expected to develop and prioritize key performance topics that identify geotechnical, foundation, and substructure issues.

- **Data needs and data gaps**—Workgroups were directed to discuss data needs and gaps related to the key performance issues identified in the first breakout session. Workgroups were expected to develop a list of data that can be currently collected, data that need to be collected during the course of the research program, and data that cannot currently be collected but would be important to the objectives of the program.

- **Tools, technology development, and monitoring**—Workgroups were directed to discuss how geotechnical performance data can be collected. Workgroups were expected to develop lists of tools and technology that are available and should be in use in the program. Workgroups were also expected to identify technology development needs to address identified data gaps.

LTBP PROGRAM

FHWA Perspective: Background on the LTBP Program

The LTBP program is a designated research program authorized under the 2005 *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users* (SAFETEA-LU).[(1)] The program was initiated in April 2008, and the anticipated duration is 20 years or more. The genesis for the LTBP program is the lack of reliable deterioration models and a quantitative performance database of roughly 500,000 bridges in the United States. The challenges to be addressed, including aging infrastructure, limited resources, increasing traffic and truck loads, stewardship and management of the existing inventory, and extreme events, were outlined. Overcoming such challenges requires innovative designs, more durable materials, advanced sensor technology, and better construction, maintenance, and rehabilitation methods. System evaluation is a necessary first step to develop a better understanding of the performance problems and issues.

The LTBP program thus established its overall goal—the development of a quantitative bridge performance database that incorporates detailed inspection, periodic evaluation, and data from representative samples of bridges, as well as legacy data from existing sources of information related to bridge performance. The desired and anticipated outcomes include improved knowledge of bridge performance; development of improved predictive and deterioration models; the means to quantify effectiveness of various maintenance, preservation, repair, and rehabilitation strategies; better tools for bridge management; and improved standards for testing and monitoring.

The initial stage and the developmental phase of the program were described. The initial stage involves stakeholder outreach, identification of available databases and knowledge gaps, and development of a strategic plan. The development phase was underway at the time of this report and involves the identification of many issues related to the challenge of defining performance and performance categories. The development phase is being augmented by a field investigation using a limited number of pilot bridges to validate protocols and processes. The field investigation will feed into the long-term data collection of a representative sample of bridges.

Fiscal year 2010 activities were reviewed and include continuing the pilot study phase, validating and refining protocols, finalizing the bridge sample size, identifying geotechnical performance issues, establishing a Transportation Research Board LTBP advisory board, establishing LTBP State coordinators, performing outreach activities, identifying reference bridges, and completing a beta test of the LTBP bridge portal, which will be the interface for the LTBP database. A few of these topics were discussed in detail in the workshop as well as the importance of the workshop to identify the geotechnical performance issues. Additionally, an overview of the LTBP program team was provided.

Contractor Perspective: Research Approach

A short introduction to the research approach was provided, beginning with a review of the program goals and the expected program outcome and following with a more indepth description of the program's strategic plan. The LTBP program goals are as follows:

- Obtain a deeper understanding of bridge performance.
- Develop and evaluate methods to reliably measure bridge performance.
- Improve the Nation's bridge infrastructure and performance of the transportation system.

The expected program outcome is improved knowledge of bridge performance in two areas: structural and functional. In the structural area, this means better understanding of bridge deterioration as well as improved predictive models, next-generation design methods, bridge preservation practices with life-cycle cost models, and next-generation bridge management systems. In the functional area, this means a better understanding of the impact that features of bridges have on traffic capacity, load capacity, and traffic safety on the bridge.

In support of these goals and outcomes, a strategic plan and LTBP road map were developed. The seven steps of the road map were described, and the current status of each step was provided. The workshop served as an opportunity to define the geotechnical experimental program and geotechnical data to be collected under the LTBP program. On the basis of the meeting, the roadmap was to be edited for geotechnical inputs to the program. The importance of the Web-based decision support tools being developed within the program and the bridge portal tool were emphasized.

Summary of Focus Group Meetings

A summary of the focus group interviews held during the first 2 years of the program was provided. The focus groups were a key tool in the effort to identify high-priority bridge performance issues and the data necessary to study these issues.

The distinction between data and knowledge in relation to performance, the difficulties in measuring bridge performance, and the current status of the U.S. bridge infrastructure were reviewed. Bridge performance was broken down into four categories: (1) structural condition (durability and serviceability), (2) functionality (user safety and service), (3) costs (to agencies and users), and (4) structural integrity (safety and stability).

The selection of study topics for the LTBP program was also reviewed. Selection was accomplished by identifying candidate knowledge gaps and developing high-priority study topics based on literature and expert solicitation. The latter portion was implemented by canvassing representative stakeholders, mainly at State transportation departments around the Nation. The expert focus groups were asked to identify the most significant bridge performance issues, current practices, current information sources, and necessary improvements. Examples of the discussions held with the focus groups were presented.

From the focus group discussions, the study topic selection proceeded by identifying the knowledge gaps from the literature and expert solicitation, creating a series of study topics to address gaps, and prioritizing the study topics by canvassing the LTBP research team, external working technical groups, and FHWA internal working groups. As a result of this process, 20 study topics were prioritized and ranked. A list of additional suggested topics was also provided. For each topic, the study needs were defined by framing a series of experimental questions, prioritizing the questions to focus the study, developing the hypothesis to be evaluated, and identifying the data needed to address the questions. An example of this approach based on untreated concrete decks was presented.

The presentation concluded by stating that the challenge of this workshop was to identify and refine study topics related to bridge substructure and foundations. The following were identified as substructure and foundation topics:

- Performance of bare/coated concrete superstructures and substructures.
- Methods to measure scour that are direct, reliable, and timely.
- Performance of scour countermeasures.

- Identification and performance of unknown foundations.
- Performance of structure foundation types.
- Performance of bridge bearings (all types).
- Performance of jointless structures (integral, semi-integral, and continuous for live load).

Summary of LTBP Pilot Program

A summary of the LTBP pilot program was provided. In the pilot portion of the program, researchers should validate protocols for data collection and management and ensure that all of the components needed to achieve the long-term objectives of the LTBP program are specified before initiating work on the large population of bridges nationwide. The pilot program objectives, bridge selection, schedule, and example information from selected pilot bridges were given. The pilot program objectives are as follows:

- Validate visual inspection, NDE, and instrumentation protocols.
- Refine and streamline inspection, testing, and instrumentation.
- Field test various methods for collecting data.
- Test and validate quality control (QC) measures, data transfer, and storage.
- Collect early useful data for the program.

Each of these objectives was discussed in more detail during the workshop.

Pilot program bridges are located in California, Florida, Minnesota, New Jersey, New York, Virginia, and Utah. The pilot program was to last 2 years beginning in early fall 2009. Kickoff and instrumentation of each bridge were supposed to be 3 to 4 months, including 2 weeks for visual inspection and NDE testing and 3 months for instrumentation, with the following activities:

- Develop an instrumentation plan.
- Develop a site plan for transportation department approval.
- Contract necessary field work.
- Perform in-place instrumentation of bridge.

Information was shared on pilot program bridges in Virginia, New Jersey, Utah, and California. Future pilot program bridges will be in Florida, Minnesota, and New York and may present an opportunity to include geotechnical-focused and hydraulics-focused topics.

Geotechnical Factors and Bridge Performance

An overview of the geotechnical aspects that affect overall bridge performance and an introduction to the breakout sessions was provided. Several examples of geotechnical issues affecting bridge performance, including mechanically stabilized earth (MSE) walls, foundations on rock, abutment issues (in particular, settlement at the bridge-abutment interface and its effects on the superstructure), and scour were given. The summary point was that the performance of geotechnical aspects of the bridge affects the overall performance of the bridge. Thus, the issue is how geotechnical issues affect holistic bridge performance. The short- and long-term aspects and the appropriate data to collect must be considered.

The breakout sessions were then introduced and the purpose of the workshop (i.e., to consider overall bridge performance and identify geotechnical performance indicators that may correspond to good and poor performance) was reiterated. The information generated was to be provided to the LTBP program as recommendations to accommodate additional data and methods to evaluate the data over time.

The focus group meetings held by the LTBP program identified several topics related to the superstructure and the bridge deck. It did not appear that geotechnical, foundation, and substructure concerns were adequately captured. The list of study topics from the focus groups had one topic on structural foundations and three topics on bridge scour and unknown foundations. Other geotechnical issues related to bridges merit consideration, which was the purpose of this workshop.

BREAKOUT SESSION I: BRIDGE PERFORMANCE ISSUES

BRAINSTORMING BRIDGE PERFORMANCE ISSUES

The first breakout session focused on identifying the key bridge performance issues related to foundations, substructures, and geotechnical features. The goal of this session was to develop and prioritize the key geotechnical issues that may affect critical aspects of bridge performance as well as performance of the bridge as a whole. The workshop participants were divided into three groups and spent the bulk of the afternoon on March 4, 2010, discussing the session topic. Following the discussion time, the participants reunited to summarize the group findings.

The participants in group 1 were as follows:

- Chris Benda (chair).
- Mike Adams.
- Ed Kavazanjian.
- Kevin O'Connor.
- Larry Jones.
- Mark Morvant.
- Derek Soden.
- Dan Ghere.
- Dennis Mertz.
- Barry Brecto.
- Jeffrey Ger.
- Curtis Monk.
- Andrew Foden.

The participants in group 2 were as follows:

- Marcus Galvan (chair).
- Scott Anderson.
- Robert Liang.

- Allen Cadden.
- Bob Kimmerling.
- Naresh Samtani.
- Jim Higbee.
- Krystal Smith.
- Bill Kramer.
- Gary Person.
- Kornel Kerenyi.
- John M. Hooks.
- Mike Brown.
- Dan Brown.
- Sandra Larson.
- Hamid Ghasemi.

The participants in group 3 were as follows:

- Brian Liebich (chair).
- Jennifer Nicks.
- Anand Puppula.
- Barry Christopher.
- Frank Jalinoos.
- Liz Smith.
- Ed Hoppe.
- Norm Wetz.
- Jan Six.
- Allen Marr.

- Ali Maher.
- Monica Starnes.
- Richard Dunne.
- Jawdat Siddiqi.

Each group approached the identification and ranking of key performance issues in a different way. The groups provided summaries of their discussions and rankings. Additional notes are provided in appendices D, E, and F for groups 1, 2, and 3, respectively.

GROUP 1

Group 1 began the discussion by developing a list of bridge performance issues. About 40 performance issues were identified that covered a broad array of topics. Next, group 1 developed a means of sorting and ranking the issues. The group created five categories into which the issues could be placed: (1) foundations, (2) abutment interface, (3) materials, (4) construction, and (5) hydraulics. The issues in each category are shown in table 1. The group then rated each of the issues within the categories using an importance rating of highest (3), medium (2), and lowest (1). More than one issue could receive each of the importance ratings (see table 1). Additional group 1 information is included in appendix D.

Table 1. Breakout session I—group 1 bridge performance issues.

Abutment Interface	Importance
Bump (between top of abutment and roadway pavement) at the end of the bridge • Lateral spreading at abutment • Joint filler failure • Dynamic load amplification on bridge • Approach slab settlement	3
Temperature loads on integral abutments	3
Integral abutment ratcheting and resulting forces	3
Behavior of shallow foundations behind MSE walls	2
Behavior of pile foundations behind MSE walls	3
Effect of grade, heavy skew, or superelevation on abutments	2
Interaction between performance of one abutment on opposite abutment	1
Foundations	**Importance**
Differential movements	1
Measured foundation loads to calibrate/refine design codes • Accurate modeling during design (effects of pile caps, etc.) • Different behavior of foundation to short- and long-term loads • Improved efficiency in foundation design • Proper combination of extreme events • Design for serviceability under lower seismic events	3
Unknown foundations	3
Effects of widening structures • Effects on existing structures • Use of different foundation types	3
Quantification of tolerable movements for design • Vertical • Lateral	3
Hydraulics	**Importance**
Accurate prediction of scour	3
Monitoring of scour	3
Monitoring of scour countermeasures	3
Effect of laterally migrating streams	1
Effect of toe erosion on slope stability	2
Drainage performance	3
Materials	**Importance**
Long-term creep of MSE walls	2
Quality of fill and effect on MSE wall performance	2
Corrosion of MSE reinforcement	2
Corrosion of piles in aggressive/corrosive environments	3
Construction of large diameter drilled shafts • Thermal stresses during construction (mass concrete)	2
Construction	**Importance**
QC during construction • Effects on long term performance of the structure • Effect of various contract methods (design-build versus design-bid-build)	3

GROUP 2

Group 2 discussed the performance factors that should be considered relative to their impact on strength, serviceability, survivability, and structural safety. In general, the group felt that problems arise when safety margins are lower than desired, loads on structures are greater than originally designed for, or capacity and stiffness have reduced over time due to substructure changes. Group 2 developed three broad categories that related the performance issues to approaches, piers, and abutments, with subcategories as necessary. Nearly 50 performance issues were identified (see table 2). To develop a rating of the performance issues, group 2 used a methodology in which each member received a certain number of votes for the categories. The relative importance of each issue within a category was established based on the number of votes received. The highest rated performance issues are summarized in table 3. The complete voting for the issues is in appendix E.

Table 2. Breakout session I—group 2 bridge performance issues.

Approaches

Embankments

- Vertical settlement
- Erosion/overtopping
- Lack or loss of support of approach slabs
- Settlement-related impacts on serviceability (bump at the end of the bridge)
- Potholes or rutting (indicative of other issues)
  - Saturation of slopes and changes in shear strength over time

Piers

General

- Vertical geotechnical bearing
- Vertical and horizontal movement or rotation
- Cracking
- Scour/erosion and loss of lateral stability, compromised protection
- Damage to foundation element caused by collision, ice flow, earthquake, or other extreme events
- Pile performance—corrosion and loss of flexural strength
- Driving stresses on piles
- Cracking and corrosion of reinforcement/strand
- Debris accumulation
- Global stability
- Differential settlement

Abutments

General

- Vertical geotechnical bearing
- Earth retention
- Drainage and filtration
- Vertical and horizontal joint movement or rotation
- Cracking
- Scour/erosion
- Impact loading
- Collision impact
- Pile performance—corrosion and loss of flexural strength
- Driving stresses on piles
- Slope protection performance, compromised protection
- Abutment influence on bearing performance (protection or support)
- Global stability
- Differential settlement
- Piping loss and migration of fines

MSE Walls

- Corrosion of metallic reinforcement
- Leakage of backfill
- Settlement

Soil-Nail Walls

- Cracking
- Corrosion of tendons
- Global stability due to changes in groundwater
- Scour/erosion
- Cracking
- Horizontal movement
- Fascia deterioration/spalling
- Drainage failure

Cast-in-Place Walls/Other

- Cracking
- Corrosion
- Scour/erosion
- Excessive displacement

Integral Abutments

- Soil restraint of abutment translation (jacking)

Table 3. Breakout session I—group 2 highest ranking bridge performance issues.

Votes	Element	Sub-Element	Performance Issue
11	Approaches	Embankments	Settlement-related impacts on serviceability (bump at the end of the bridge)
10	Approaches	Embankments	Global stability (slope failure)
14	Piers	General	Scour/erosion and loss of lateral stability, compromised protection
13	Piers	General	Total and differential settlement
11	Piers	General	Horizontal movement or rotation
11	Abutments	General	Vertical and horizontal joint movement
11	Abutments	General	Total and differential settlement
8	Abutments	General	Scour/erosion
8	Abutments	General	Pile performance—corrosion, loss of flexural strength
11	Abutments	MSE walls	Corrosion/degradation of reinforcement
10	Abutments	MSE walls	Drainage failure
14	Abutments	Soil-nail walls	Corrosion of tendons
8	Abutments	CIP walls/other	Scour/erosion
5	Abutments	CIP walls/other	Excessive displacement
12	Abutments	Integral abutments	Soil restraint of abutment translation (jacking)

CIP = Cast-in-place.

GROUP 3

Group 3 brainstormed for about 15 min, suggesting one- and two-word descriptions of performance issues to capture the complete spectrum of possible problems. The resulting list is shown in table 4. The group then discussed which of the issues were of primary importance, which is highlighted in bold in the table. The group then categorized the performance issues into movement/deflections, safety/usability, material performance, soil structure interaction, construction, recertification/reassurance, or drainage/runoff/erosion. Subcategories were developed in some cases. To differentiate between the performance issues, the group considered four metrics for each category or subcategory: (1) the likelihood of the issue developing, (2) the safety implications of the issue, (3) the effect of the issue on bridge serviceability, and (4) the cost of the issue. Each metric was then rated on a 1 to 3 scale where 1 is low and 3 is high. The ratings were assigned to each metric to create a score for each category or subcategory. The summary list of priority issues developed from this system is as follows:

1. Corrosion/deterioration (MSE walls, steel in piles, and embankment material).

2. Bump at the end of the bridge.

3. Fatigue/integral abutment/lateral stress.

4. Drainage/runoff/erosion.

In addition, the group indicated that two topics were important to keep in mind relative to the performance issues: ongoing bridge inspection and less frequent extreme event evaluations. The complete group 3 performance issues list and metric ratings are in appendix F, along with a summary of the group's discussion.

Table 4. Breakout session I—group 3 bridge performance issues.

Corrosion	Monitoring technologies	Backfill test methods	Ground water fluctuations
Freeze-thaw	Data management	Compaction	Post extreme event assessment
Approach slab	Creep	**Differential settlement**	Seismic shift impact
Post-disaster assessment	New foundation systems	Tolerable settlement	Laser scanning
Settlement	**Drainage**	**Deterioration**	Foundation surveys
Collapse	**Runoff**	Seasonal changes	**Maintenance records**
MSE walls	Instrumentation practices	Widening of bridge approaches	Erosion
Movement/displacement	Surficial slope stabilization	Loads	**Safety**
Lateral stress	Ground improvement	Unsaturated soils	Stream degradation
Swelling soils	Reinforced slopes	Construction QA/QC	Land use changes
Slope stability	Lightweight fill	As-built documents	Owner education
Corrosive soils	Foundation types	Smart structures	Phase construction
Unknown foundations	Reliability	Structural resistance	Accelerated construction
Scour	Redundancy	Unanticipated subsurface soils	Settlement control
Construction	Risk	Geophysics	Mitigation
Connection details	Performance	Damage left in place	Fatigue
Deep soft soils	Spread footings	Site variability	**Bump at end of bridge**
Strain incompatible	Nominal resistance	Satellites—GPS and light detection and ranging (LIDAR)	
Symptoms versus problems	Factor resistance		
What to measure	Change in original assumptions		
NDE			

QA = Quality assurance.
GPS = Global Positioning System.
Note: Bold text indicates issues determined to have highest importance.

SUMMARY—BRIDGE PERFORMANCE ISSUES

Following the brainstorming session on bridge performance issues, the lists and priorities from the three groups were collected and reviewed. Despite different approaches to identify and rate the importance of the issues, the groups generally identified the same issues and priorities. A summary of the priorities identified by each group was prepared and presented to all workshop participants on the morning of March 5, 2010 (see table 5). Each group identified performance issues related to the approach in terms of the bump at the end of the bridge, integral abutments, settlement of abutments and piers, material corrosion, scour, and QC/quality assurance (QA).

Table 5. Summary of priority issues identified by each group in breakout session I.

Group 1	Group 2	Group 3
• Abutments: Bump at end of bridge, integral abutments, and piles • Foundations: Measured loads, widening, unknown foundations, and tolerable movements • Hydraulics: Scour and drainage • Materials: Corrosion • Construction: QC	• Approaches: Settlement and global stability • Piers: Scour, total differential settlement, and horizontal movement • Abutments: Vertical and horizontal joint movement, differential settlement, scour, and pile performance • Abutment walls: Corrosion, drainage failure, scour, and soil restraint	• Corrosion/deterioration (MSE walls, steel in piles, and embankment material) • Bump at end of bridge (significant) • Fatigue/integral abutment/lateral stress • Drainage/runoff/erosion • Remaining service life—long-term performance

BREAKOUT SESSION II: DATA NEEDS AND GAPS

BRAINSTORMING DATA NEEDS AND GAPS

The second breakout session focused on discussing the data needs and gaps related to the key performance issues identified in the first breakout session. The goal of this breakout session was to develop a list of data that can be currently collected, data that need to be collected during the course of the research program, and data that cannot currently be collected but would be important to the objectives of the program. Similar to the first breakout session, the workshop participants were divided into three groups. While the chair of each group remained the same, the participants in each group were changed. The groups spent the majority of the morning on March 5, 2010, discussing the session topic. Following the discussion time, the participants reunited to summarize the individual group findings.

The participants in group 1 were as follows:

- Chris Benda (chair).
- Mike Adams.
- Anand Puppula.
- Allen Cadden.
- Ed Hoppe.
- Derek Soden.
- Liz Smith.
- Bill Kramer.
- Barry Brecto.
- Frank Jalinoos.
- Jawdat Siddiqi.
- Andrew Foden.

The participants in group 2 were as follows:

- Marcus Galvan (chair).
- Scott Anderson.
- Ed Kavazanjian.

- Barry Christopher.
- Bob Kimmerling.
- Kevin O'Connor.
- Larry Jones.
- Jan Six.
- Dan Ghere.
- Dennis Mertz.
- Curtis Monk.
- Monica Starnes.
- Mike Brown.
- Mark Morvant.

The participants in group 3 were as follows:

- Brian Liebich (chair).
- Jennifer Nicks.
- Robert Liang.
- Dan Brown.
- Allen Marr.
- Naresh Samtani.
- Jim Higbee.
- Gary Person.
- Norm Wetz.
- Kornel Kerenyi.
- John M. Hooks.
- Jeffrey Ger.

- Sandra Larson.
- Ali Maher.

As with the first breakout session, each group approached the identification and ranking of data needs and gaps in a different way. The groups provided a summary of their discussions and rankings.

GROUP 1

Group 1 developed data needs for four bridge performance issues: (1) the bump at the end of the bridge, (2) corrosion/deterioration (including MSE walls, piles, and soil), (3) foundations, and (4) hydraulics. The group also provided an assessment of the data needs using the following codes:

- **A**: Data needs that are generally available (i.e., weather data, construction records, and maintenance records).
- **M**: Data that the group felt could be collected or measured with existing technology and tools during the course of the research program (i.e., water table elevation and changes in foundation stiffness over time).
- **G**: Data that the majority of the group believed could not be reasonably collected with currently available technology (i.e., diffusion rate of chloride) but were considered important to the overall goals of the program (data gaps).

Table 6 through table 9 list the data needs that the group identified for the four bridge performance issues.

Where dual letters are shown, the group felt the identified data need fell into more than one category depending on a variety of circumstances. For example, the load or strain on a facility (abutment) or element within the facility (pile) can be measured now (M) if instrumentation was installed during construction. The same attributes on this facility would be difficult to obtain (G) for a variety of technical and logistical reasons if the instrumentation was not installed during construction.

Table 6. Group 1 data needs for bump at the end of the bridge.

Data Needs	Category
Rideability/profiler	M
Traffic (ADT and ADTT)	A
Construction records and foundation report	A
Weather data	A
Elevation survey	M
Bridge type/abutment	A
As-built plans/details	A
Post-construction instrumentation monitoring records	G
Integrity of embankment—vertical and lateral movement	M
Integrity of foundation subsoil—vertical and lateral movement	M
Loads on retaining walls	M/G
Dynamic loads on structure	M
In situ and fill soil conditions	A/M
Soil strain signature	M/G
Abutment movements	M
Water table info	M
Soil erosion and loss	M
Cyclic strain (freeze-thaw/heaving)	M
Depth of influence of truck loads	M
Approach pavement info	A
Approach transition detail	A

ADT = Average daily traffic.
ADTT = Average daily truck traffic.

Table 7. Group 1 data needs for corrosion and deterioration.

Data Needs	Category
Ground water corrosivity	M
Soil corrosivity	M
Winter maintenance practice	A
Stray electric currents	M
Weather data	A
Backfill type and testing procedures	A
Surface drainage	M
Water table elevation and fluctuation	M
Corrosion and conditions of connection in MSE walls	M
Visual indications of corrosion on wall face	A
Visual indications of corrosion on piles	A
Corrosion rates	G
Section loss	M/G
Properties of foundation element (properties, coatings on steel)	A
Condition of foundation element (properties, coatings on steel)	M
Diffusion rate of chloride	G
Deterioration of timber piles	M

Table 8. Group 1 data needs for foundations.

Data Needs	Category
Construction records, foundation report	A
Bridge type/abutment	A
As-built plans/details	A
Strain distribution along element with time	G
Foundation type/materials	A
Subsurface information	A
Water table elevation and fluctuation	M
Existing capacity	G
Geometry	A
Integrity of element	G
Foundation stiffness and changes over time	M
Element vertical and lateral movements	M
Correlating superstructure forces/behavior/movement	M
Baseline survey data	M/G
Weather data	A
Ice thickness and properties	M
Stress/strain in MSE reinforcement	M/G
Measured earth pressure on wall/abutment	M/G

Table 9. Group 1 data needs for hydraulics, scour, and drainage.

Data Needs	Category
Construction records and foundation report	A
Bridge type/abutment	A
As-built plans/details	A
Weather data	A
Design scour	A/G
Measured scour (real time and/or post-event)	M/G
Stream velocity/flow rate	M
Countermeasure type and current condition	A/M
Subsurface information	A
Changes in land use	A
Stream bed profiles/cross section	M
Debris accumulation and removal	M/G
Countermeasure maintenance records	A/G
Channel stability and migration	M/G
Historical storm and flow data	A/G
Photo records	A/M
Abrasion and impact damage	M
Drainage system and condition	M
Ground cover and stabilization on side slopes	M
Hydraulic impacts of structure on stream flow (hydraulic cap)	M
Water table elevation and fluctuation	M
Effectiveness of stream training	M
Dynamic response of bridge during flood events	M
Erosion impact on global stability	M
Element vertical and lateral movements	M

Unlike other breakout sessions, all relevant material from group 1 deliberations in breakout session II is included in this section. Therefore, there is no appendix for additional information from group 1 for this breakout session.

GROUP 2

Group 2 discussed the data that are currently gathered and the wanted or needed measurements and then mapped the data to performance issues. The data that are currently gathered primarily come from National Bridge Inspection program forms and are rather limited in application to geotechnical assets. The wanted or needed measurements are more encompassing. Group 2 developed a list of 19 pieces of wanted or needed data and mapped them to a list of 12 performance issues. The frequency of the data measurement was defined in terms of timing of the acquisition of the data as original (when constructed), a periodic measurement, or a continuous measurement. Additionally, the group rated the data measurement as available, obtainable, future, or not obtainable, which is highlighted in further detail in appendix G. Wanted or needed measurements include the following:

- Magnitude and rate of settlement at approach-bridge transition.
- Voids under approach slab.
- Vertical and lateral deformations at grade along length of bridge.
- Channels profiles.
- Quality geotechnical data:
    - More than bore logs.
    - Strength and compressibility data.
    - Ground water table.
    - Chemical properties (sulfates/chlorides/resistivity/pH).
    - Expansion potential.
    - Freeze-thaw classification.
- QC records from construction.
- As-built information—detailed element location (vertical and horizontal).
- Climate data:
    - Temperature.
    - Precipitation.
    - Storm runoff.
- Loads and stresses in piles and drilled shafts.

- Lateral earth pressures and swell pressures.
- Rideability index at transitions (similar to International Roughness Index (IRI)).
- Vibration monitoring—ambient or forced vibration to observe changes in fundamental vibration modes.

GROUP 3

Group 3 developed data needs for eight bridge performance issues: the bump at the end of the bridge, corrosion, scour/hydraulics, integral abutments/soil-structure interaction, drainage/runoff, QA/QC, foundations, and earth-retaining structures. For these performance issues, group 3 identified 4 to 10 data needs for 59 data need items. Table 10 through table 17 show the data needs identified by group 3. Additional information about group 3 can be found in appendix H.

Table 10. Group 3 data needs for bump at the end of the bridge.

Data Needs
Vertical settlement at abutment
Slope
Vertical settlement profile with depth
Changes over time
Lateral movement
Maintenance records
Moisture info/profile in soil
Increase load
Freeze-thaw/heave
Deterioration of geofoam/non-soil embankment materials

Table 11. Group 3 data needs for corrosion.

Data Needs
Chloride/sulfate concentrations and corrosivity
Resistivity, pH
Current condition (physical, MSE corrosion test strip)
Moisture water
Change over time/stiffness
Construction records
Concrete mix design
Deterioration of geofoam/non-soil embankment materials
Deicing usage/maintenance records

Table 12. Group 3 data needs for scour/hydraulics.

Data Needs
Scour/scour evolution
Horizontal/vertical velocity/water depth
Horizontal/vertical channel bed profile
Movement of riprap
Hydrodynamic load
Changes in debris/mining

Table 13. Group 3 data needs for integral abutments/soil-structure interaction.

Data Needs
Cracking/spalling
Differential movement
Temperature
Joint closure/buckled approach sections

Table 14. Group 3 data needs for drainage and runoff.

Data Needs
Dye tracking
Volume—weir
Precipitation
Changes in land use/vegetation
Deflections on abutment, erosion
Location and condition—drainage pipes/materials
Presence and magnitude of voids
Corrosion of exposed elements
Visual observations

Table 15. Group 3 data needs for QA/QC.

Data Needs
Historic records
Project close-out reports
Concrete sampling records
Pile driving records
Change in structural stiffness
Damage left in place
Load test info

Table 16. Group 3 data needs for foundations.

Data Needs
Historic records
Unknown foundation quantification
Integrity after extreme event
Nearby construction, changes in geometry
Visible inspection, including National Bridge Inventory
Measure of internal forces within structure

Table 17. Group 3 data needs for earth-retaining structures.

Data Needs
Differential movement (horizontal, vertical, and lateral rotations)
Surface cracking/spalling
Ground water pressures
Drainage conditions, weep holes, etc.
New global stability issues
Gaps or cracks in soil behind wall
Corrosion of wall elements
Expansive soils

SUMMARY—DATA NEEDS AND DATA GAPS

Following the brainstorming session on data needs and gaps during the morning of March 5, 2010, the lists and priorities from the three groups were presented to the larger group. There was considerable overlap in the data needs developed by the three groups. However, more work was needed to determine the meaning of the lists. Thus, the data needs and gaps were not discussed in detail at the workshop.

The benefit of the data needs and gaps session was that participants identified a comprehensive list of data needs and, in some measure, data gaps. It is recommended that a follow-up task group be formed to formulate research needs related to data needs and gaps for the LTBP program.

BREAKOUT SESSION III: TOOLS, TECHNOLOGY DEVELOPMENT, AND MONITORING

BRAINSTORMING TOOLS, TECHNOLOGY DEVELOPMENT, AND MONITORING

The third breakout session focused on how geotechnical performance data can be collected. The goal of this breakout session was to develop lists of tools and technologies that are currently available and should be used in the LTBP program and to identify technology development needs to address identified data gaps. As in the previous sessions, the workshop participants were divided into three groups. While the chair of each group remained the same, the participants in each group changed. Each group spent the early afternoon on March 5, 2010, discussing the session topic. Following the discussion time, the participants reunited to summarize the individual group findings.

The participants in group 1 were as follows:

- Chris Benda (chair).
- Mike Adams.
- Robert Liang.
- Dan Brown.
- Barry Christopher.
- Naresh Samtani.
- Jim Higbee.
- Gary Person.
- Jan Six.
- Kornel Kerenyi.
- John M. Hooks.
- Monica Starnes.
- Andrew Foden.
- Sandra Larson.

The participants in group 2 were as follows:

- Marcus Galvan (chair).
- Scott Anderson.
- Anand Puppala.
- Allen Marr.
- Bob Kimmerling.
- Jorge Pagán-Ortiz.
- Ed Hoppe.
- Norm Wetz.
- Liz Smith.
- Barry Brecto.
- Frank Jalinoos.
- Jawdat Siddiqi.
- Mike Brown.

The participants in group 3 were as follows:

- Brian Liebich (chair).
- Jennifer Nicks.
- Ed Kavazanjian.
- Allen Cadden.
- Kevin O'Connor.
- Larry Jones.
- Bill Kramer.
- Mark Morvant.
- Dan Ghere.

- Dennis Mertz.
- Jeffrey Ger.
- Curtis Monk.
- Derek Soden.
- Ali Maher.

As with the previous breakout sessions, each group approached the identification and matching of tools and technology development needs to performance issues and data needs and gaps in a different way. The groups provided summaries of their discussions and lists of tools and development needs. Notes are provided in appendices I, J, and K for groups 1, 2, and 3, respectively.

GROUP 1

Group 1 developed a list of the availability of the tools/technology for the four bridge performance issues for which the group had previously developed data needs and gaps: (1) the bump at the end of the bridge, (2) corrosion/deterioration (including MSE walls, piles, and soil), (3) foundations, and (4) hydraulics. Thus, for the 21 data needs for the bump at the end of the bridge, the group identified existing and future means of measuring the specific data of interest. The group also did this for the 17 data needs identified for corrosion/deterioration, the 18 data needs identified for foundations, and the 25 data needs identified for hydraulic issues. Where possible, the group identified the availability of tools/technology for specific data needs. The resulting list is in appendix I.

GROUP 2

Group 2 took a slightly different approach on this topic. The group developed the following categories in which similar types of data or information would be collected: environment, visual/hands-on inspections, movements at surface, movements at depth, groundwater and river water level, moisture content profile, historical records, subsurface information, deterioration rates, and on-demand monitoring. Based on these categories, the group listed tools that would be appropriate for measuring/collecting various types of data or information. For each type of data listed, the group provided an assessment of whether the tools/technology are currently obtainable (tools/technology exists and is readily deployable) or are a future development (tool/technology not yet available or not yet practical). The complete list of tools/technologies mapped to the categories is in appendix J.

GROUP 3

Group 3 used the eight bridge performance issues developed for the data needs/gaps session and developed tables for each of the issues, providing lists of currently available tools/technology, near-future tools/technology, and long-term tools/technology for each performance issue. These lists are in appendix K and cover a wide range of tools/technologies. The lists demonstrate that many devices are in use for collection of data, and there are some very promising tools/technology on the horizon for near-future and long-term use. The group provided a list of the most important new, emerging, and needed technologies, including integrating nanotechnology, laser/radar interferometry monitoring of deflection, micro-electrical-mechanical systems (MEMS), smart foundation elements, biosensors, biocementation, energy piles (to keep from applying salt), airborne imagery, smart soils, smart elements to record load history, and embedded Global Positioning System (GPS) reference points.

SUMMARY—TOOLS, TECHNOLOGY DEVELOPMENT, AND MONITORING

Following the afternoon brainstorming session on March 5, 2010, on tools, technology development, and monitoring, the lists and assessments from the three groups were presented to the larger group. As with the data needs and data gaps session, it was apparent that there was considerable overlap in the tools/technologies identified by the three groups. It was also apparent that considerably more work would be needed to sort out the meaning of the lists. Thus, the tools, technology development, and monitoring were not discussed in detail at the workshop.

The benefit of the tools, technology development, and monitoring session was that participants identified a comprehensive list of tools and technologies for data collection and, in some measure, mapped the tools/technologies to specific data needs as well as future and long-term needs. Thus, the workshop provided a good starting point for further efforts in identifying and matching tool/technologies to data needs. It is recommended that a follow-up task group be formed to better define the tools, technology development, and monitoring of geotechnical-related bridge assets for the LTBP program.

POST-WORKSHOP DISCUSSION SESSION

On the morning of March 6, 2010, FHWA personnel, the LTBP research team, and the breakout session chairs met to discuss the results of the sessions, discuss workshop report preparation, and outline the path forward.

The attendees of the post-workshop discussion session were as follows:

- Jorge Pagán-Ortiz, FHWA.
- Mike Adams, FHWA.
- Chris Benda, Vermont Agency of Transportation (AOT).
- Dan Ghere, FHWA.
- Brian Liebich, California Department of Transportation (Caltrans).
- Silas Nichols, FHWA.
- Vern Schaefer, Iowa State University.
- Hamid Ghasemi, FHWA.
- Scott Anderson, FHWA.
- Marcus Galvan, Texas Department of Transportation (TxDOT).
- Kornel Kerenyi, FHWA.
- Ali Maher, Rutgers/ Center for Advanced Infrastructure and Transportation (CAIT).
- Jennifer Nicks, FHWA.
- Derek Soden, FHWA Florida Division.

The early discussion was general and focused on trying to put the geotechnical workshop in focus with the LTBP program. An emphasis was that proposed efforts must meet the needs of the LTBP program. The findings of the workshop can address issues of interest to the LTBP program, but other issues will arise as a result of the workshop that are outside the scope of the LTBP program. As a result of the workshop, short-term (3–5 years) and long-term (5+ years) geotechnical opportunities should be identified.

For geotechnical bridge performance issues identified at this workshop, the original 20 study topics identified by the focus groups provide a logical starting point for consideration by the LTBP program (see appendix C). For each of the original 20 study topics, a review and brief summary of the state of practice, previous research, and identification of remaining questions that can be addressed under the LTBP program has been prepared. Topics identified from this workshop can potentially be added to the current list of study topics. Seven of the twenty study topics are related to the deliberations at this workshop, including performance of structure foundation types; direct, reliable, and timely methods to measure scour; and performance of scour countermeasures. The performance issues identified in this workshop can be considered additions or clarifications to the study topics list as the list is refined and additional information is gathered from stakeholders.

The next topic of discussion was the pilot program and reference bridges. The pilot program focused on detailed inspection and monitoring of seven bridges to validate protocols and processes. The LTBP program was in the middle of the pilot program, which had not included geotechnical aspects. Three more pilot program bridges offered an opportunity to include geotechnical aspects. The reference bridges were to be identified for long-term monitoring under the LTBP program. These bridges were in the process of being identified at the time of this report, and opportunities existed for inclusion of geotechnical-related performance monitoring on these bridges.

Opportunities also exist to include geotechnical performance aspects in bridges being considered in the pilot program in Minnesota, New York, and Florida. It was noted that many of the geotechnical performance issues relate to integral abutment bridges and associated retaining structures and that it would be beneficial to include retaining systems in future studies. Also emphasized was the importance of scour, which is costing States a considerable amount of money because the design of the foundation elements needs to address not only the foundation loads but also the predicted scour envelope. Many times, the scour prediction results in deeper foundations.

Based on the session I brainstorming and the post-workshop discussions, the following short-term bridge performance priorities emerged:

- Approach/bridge interface issues.
- Material degradation/corrosion/deterioration issues.
- MSE wall issues—material degradation and assessment of wall integrity.
- Hydraulics—scour, erosion, and drainage.

From the results of this workshop and other available information, these issues can be considered for inclusion on the LTBP list of study topics. Each issue will have to be further studied for the state of practice, related research, and identification of key questions that might be addressed under the LTBP program.

The long-term issues require additional time and consideration in light of the information collected at the workshop. As a starting point, the following potential long-term topics were identified:

- Future instrumentation devices and their evaluation (requires advice from other disciplines and sensor specialists).
- Innovative materials, lightweight fills, recycled materials, and environmental and carbon footprint issues.
- Geotechnical factors related to bridge serviceability and degradation models.
- Remaining service life assessment, both on geotechnical aspects and structural aspects.
- Post-hazard event diagnostic tools.

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

RESULTS

The primary objectives of the workshop were to consider overall bridge performance and identify geotechnical performance metrics or indicators that may correspond to good or poor performance. The workshop was expected to provide the LTBP program with the necessary information to identify, prioritize, and address substructure and foundation performance issues. In addition, the workshop findings were expected to provide valuable information on available tools and technologies for bridge assessment and monitoring. The objectives and expected outcomes were accomplished through brainstorming sessions in which participants discussed the following key topics:

- Bridge performance issues.
- Data needs and data gaps.
- Tools, technology development, and monitoring.

To a considerable degree, the following objectives of the workshop were achieved:

- Participants identified the key geotechnical aspects affecting overall bridge performance.
- Participants identified many data needs and data gaps as well as currently used tools to gather data and future technologies affecting data collection.
- A consensus was developed on the short-term geotechnical priorities that the LTBP program should consider in its remaining pilot bridges and reference bridges.

As a result of the session I brainstorming and the post-workshop discussions, short-term bridge performance priorities were identified. These priorities can be summarized in four categories with subcategories. For each of the performance issues, assessments of the cause and effect of the issue, the QC/QA aspects, the detection/monitoring aspects, and the remedial actions to overcome the issues need to be completed.

Approach/bridge interface issues include the following:

- Settlement (including foundation and fill settlements), erosion of toe fills, poor material quality, and substandard construction practices.
- Integral abutments, temperature loads, and ratcheting effects.

Material degradation/corrosion/long-term deterioration issues include the following:

- Piles, concrete, steel, and salt water effects.
- Metallic inclusions (i.e., soil nails and anchors).
- Aggressive soils.

MSE wall issues (material degradation and assessment of wall integrity) include the following:

- Degradation of reinforcement, including deterioration and creep.
- Deformation of MSE walls.
- Quality of backfill.
- Leakage of backfill.

Hydraulics issues include the following:

- Scour (this was previously identified as a high-priority bridge performance issue during focus group meetings).
    - Direct, reliable, and timely methods to measure scour.
    - Performance of scour countermeasures.
- Drainage, joint infiltration, weep holes, and underdrains.
- Erosion, approach embankments, and from behind cast-in-place (CIP) walls.

From the results of this workshop and other available information, these issues can be considered for inclusion on the LTBP list of study topics. Each issue should be further studied for the state of practice, related research, and identification of key questions that might be addressed under the LTBP program.

As a result of the session II brainstorming and the post-workshop discussions, data needs can be summarized for the short-term bridge performance issues identified. Categories of the data needs are similar across the four performance categories and are listed in table 18. Sample data needs are shown for each performance issue and category of data needs. Additional information on data needs is contained in the session II summary and the appendices.

Table 18. Summary of sample data needs.

Performance Issue	Data Needs: Construction Records	Inspection and Maintenance History	Characterization of Service Environment	Post-Construction Monitoring
Approach/bridge interface	• As-built plans • Foundation report	• Inspection reports • Photos • Voids under slabs • Winter maintenance practices	• Climate data • Traffic • Loads	• Settlement • Rideability • Deformations • Vibrations
Material degradation	• As-built plans	• Inspection reports • Winter maintenance practices	• Climate data • Groundwater information • Soil characteristics	• Corrosion detection • Condition of foundation elements
MSE walls	• As-built plans	• Visual indications of corrosion	• Climate data • Indications of water	• Soil corrosivity • Water corrosivity
Hydraulics	• As-built plans • Abutment/pier type • Channel capacities	• Historical flow data • Channel stability and migration	• Climate data • Ice data • Stream velocity	• Post-flood records • Measured scour

As shown in the table, some data needs, such as as-built plans and climate data, cut across all performance issues. Such categories cover a lot of information requirements. For example, climate data include temperature, precipitation, wind, etc. The four data needs categories listed in the table provide a starting point for better categorization and delineation of the data needs with respect to bridge performance issues.

The workshop participants did an outstanding job of identifying the data needs. The identification of data gaps and the session III brainstorming on tools, technology development, and monitoring produced a less focused outcome relative to these issues. The appendices contain the information gathered as part of these sessions, but sorting out this information relative to the bridge performance issues and data needs requires effort beyond the scope of this report.

CONCLUSIONS

This workshop identified many geotechnical topics related to bridge performance. Based on the materials presented in this report, the following conclusions can be drawn:

- This workshop identified many geotechnical research needs that would benefit from future research.
- This workshop identified many data needs, some of which are presently available and some of which are not. The workshop also identified many technology gaps, tools, technology development, and monitoring techniques that are applicable to the data needs.

- The four high-priority short-term study topics identified can be incorporated into the LTBP list of long-term bridge performance suggested study topics (see appendix C). The long-term geotechnical study topics can be incorporated into present and future FHWA initiatives.

- The workshop achieved its objective of providing useful input to the LTBP program on the geotechnical aspects of bridge performance.

RECOMMENDATIONS

The short-term issues identified should be incorporated into the present list of long-term bridge performance suggested study topics (see appendix C).

The long-term issues identified should be incorporated into FHWA pending and future research initiatives.

APPENDIX A. AGENDA FOR FHWA GEOTECHNICAL WORKSHOP

FHWA Workshop to Identify Bridge Substructure Performance Issues

LTBP Geotechnical Workshop Agenda

Thursday, March 4th, 2010

7:00–8:00	Continental Breakfast, *Pre-Function South*
8:00–8:15	General Session/Welcome Remarks, *Pacifica Ballroom 1*
8:15–8:30	Participant Introductions
8:30–9:00	LTBP Program Overview
9:00–9:45	Summary of Focus Group Meetings
9:45–10:15	Break, *Pre-Function South*
10:15–10:45	LTBP Pilot Program Overview
10:45–11:15	Geotechnical Factors and Bridge Performance
11:15–11:45	Workgroup I Assignments
11:45–1:00	Lunch, *Promenade Deck*
1:00–5:00	Breakout Session I: Bridge Performance Issues *Group 1: Timor Sea 1* *Group 2: Timor Sea 2* *Group 3: Banda Sea 3*

Friday, March 5th, 2010

7:00–8:00	Continental Breakfast, *Pre-Function South*
8:00–8:30	Workgroup II Assignments, *Pacifica Ballroom 1*
8:30–11:30	Breakout Session II: Data Needs and Data Gaps *Group 1: Timor Sea 1* *Group 2: Timor Sea 2* *Group 3: Banda Sea 3*
11:30–1:00	Lunch, *Promenade Deck*
1:00–1:30	Workgroup III Assignments, *Pacifica Ballroom 1*
1:30–4:30	Breakout Session III: Tools, Technology, Development, and Monitoring
4:30 – 5:00	Closing Remarks

Saturday, March 6th, 2010

7:30–8:30	Continental Breakfast, *Pre-Function South*
9:00–12:00	Post-workshop Discussions (Internal FHWA), *Pacifica Ballroom 1*

APPENDIX B. GENERAL INFORMATION FOR ATTENDEES

The following information was provided to the attendees at the beginning of the workshop. It details the objective of the workshop, expected outcomes, background, breakout sessions, and a list of invited attendees.

IDENTIFYING BRIDGE SUBSTRUCTURE AND FOUNDATION PERFORMANCE ISSUES—GENERAL INFORMATION

In preparation for the LTBP workshop, "Identifying Bridge Substructure and Foundation Performance Issues," the workshop organizers are providing some general information on what to expect once you arrive. For additional information and background on the program, please visit the program's Web site at http://www.fhwa.dot.gov/research/tfhrc/programs/infrastructure/structures/ltbp/.

Dress Code

The dress code for the workshop will be casual. Please dress comfortably for the workshop and leave your ties at home.

Objective

The purpose of the workshop is to consider overall bridge performance and identify geotechnical performance metrics or indicators that may correspond to good and poor performance.

Expected Outcome

The workshop will be providing the LTBP program with the necessary information to identify, prioritize, and address substructure and foundation performance issues. The findings will also provide valuable information on available tools and technologies for bridge assessment and monitoring.

Background

FHWA is facing significant challenges in management of the Nation's nearly 600,000 bridges. The LTBP program was designated under the SAFETEA-LU authorization legislation in 2005 and developed by the FHWA Office of Infrastructure Research and Development as a 20-year strategic research program intended to collect, analyze, and evaluate scientific quality data from the Nation's bridges. The information collected as part of the program will provide a detailed picture of bridge health, improve knowledge of holistic bridge performance, and set the groundwork for the next generation of asset management.

Currently, the program is conducting a series of focus group meetings with State highway agencies and a pilot study program that consists of detailed monitoring, inspection, and testing of a small sample of bridges around the country. The primary goal of the pilot study is to validate procedures for data collection. In addition, the study will ensure that all components needed to achieve the long-term objectives of the LTBP program are specified before starting the nationwide study. Detailed monitoring, inspecting, and testing of bridges will be a major focus of the LTBP program and will include visual inspection, NDE testing and evaluation, instrumentation and monitoring, forensic autopsies of decommissioned bridges, and development of accelerated testing facilities.

The primary purpose for the focus group meetings was to identify key performance topics that are most relevant to support the objectives of the LTBP program. The focus group meetings were used to gather information related to common modes of deterioration for bridges, common maintenance activities, performance measures used to gauge to agency success in bridge management, and information required for program and project decision support.

The focus groups identified several key performance issues related to deck and superstructure performance (i.e., joints, bearings, etc.). These performance issues will be presented briefly on Thursday morning. The intention is for all participants to have an unbiased opinion on bridge performance issues before the workshop.

Breakout Sessions

There will be three sets of breakout sessions designed to generate creative thought and advanced solutions for holistic bridge performance. To maximize potential input, all participants will participate in the following three breakout sessions:

- Bridge performance issues—Workgroups will discuss key performance issues related to substructure and foundation. They are expected to develop and prioritize key performance topics that identify geotechnical, foundation, and substructure issues.

- Data needs and data gaps—Workgroups will discuss data needs and gaps related to the key performance topics. Workgroups are expected to develop a list of data needs that can be currently collected, data that needs to be collected during the course of the research program, and data that cannot be collected today but would be important to the objectives of the program.

- Tools, technology development, and monitoring—Workgroups will discuss how geotechnical performance data can be collected. Workgroups are expected to develop lists of tools and technology that are available today and should be in use with the program. In addition, workgroups should identify technology development needs to address identified data gaps.

At the conclusion of the workshop, the chair of each session will meet to discuss the results generated by the workgroups and initiate report preparation.

Invited Attendees

The list of invited attendees for this workshop is provided in table 19. The attendees were selected to provide a broad range of experience, education, and geography. The attendees represent State highway agencies; FHWA Federal aid, Federal lands, and research; academia; and consulting. In addition, the list includes a cross section of structural, geotechnical, and hydraulics engineers. The hope is that this mix will generate some creative and interesting discussion on the proposed topics.

Table 19. Invited attendee list.

No.	Last Name	First Name	Affiliation
1	Adams	Mike	FHWA Turner-Fairbank Highway Research Center (TFHRC)
2	Anderson	Scott	FHWA Resource Center
3	Benda	Chris	Vermont AOT
4	Brecto	Barry	FHWA Division
5	Brown	Dan	Dan Brown & Associates
6	Brown	Mike	Virginia Department of Transportation (VDOT)
7	Burrows	Shay	FHWA Resource Center
8	Cadden	Allen	Schnabel Engineers
9	Christopher	Barry	Consultant
10	Cooling	Tom	URS Corporation
11	Drda	Tom	FHWA Division
12	Dunne	Richard	New Jersey Department of Transportation
13	Foden	Andrew	Parsons Brinckerhoff
14	Ger	Jeffrey	FHWA Division (Florida)
15	Galvan	Marcus	TxDOT
16	Ghere	Dan	FHWA Resource Center
17	Higbee	Jim	Utah Department of Transportation
18	Hooks	John M.	Consultant
19	Hoppe	Edward	VDOT
20	Ibrahim	Firas	FHWA TFHRC
21	Jalinoos	Frank	FHWA TFHRC
22	Johnson	Bruce	Oregon Department of Transportation
23	Jones	Larry	Florida Department of Transportation
24	Kavazanjian	Ed	Arizona State University
25	Kerenyi	Kornel	FHWA TFHRC
26	Kimmerling	Bob	PanGEO, Inc.
27	Kramer	Bill	Illinois Department of Transportation
28	Larson	Sandra	Iowa Department of Transportation
29	Liang	Robert	University of Akron
30	Liebich	Brian	Caltrans
31	Macioce	Tom	Pennsylvania Department of Transportation
32	Maher	Ali	Rutgers University
33	Marr	Allen	Geocomp Corporation
34	Mertz	Dennis	University of Delaware
35	Monk	Curtis	FHWA Division
36	Morvant	Mark	Louisiana Department of Transportation and Development
37	Nicks	Jennifer	Former Ph.D. student at Texas A&M (recently hired by FHWA TFHRC)
38	Nusiarat	Jamal	E.L. Robinson
39	O'Connor	Kevin	GeoTDR, Inc.
40	Pagán-Ortiz	Jorge	FHWA TFHRC
41	Penrod	John	FHWA TFHRC
42	Person	Gary	Minnesota Department of Transportation
43	Puppala	Anand	University of Texas-Arlington
44	Samtani	Naresh	NCS Consultants
45	Schafer	Vern	Iowa State University
46	Siddiqi	Jawdat	Ohio Department of Transportation
47	Six	Jan	Oregon Department of Transportation
48	Smith	Liz	Terracon, Inc
49	Starnes	Monica	Strategic Highway Research Program 2
50	Withiam	James	D’Appolonia Engineers

51	Nichols	Silas	FHWA Headquarters
52	Ghasemi	Hamid	FHWA TFHRC
53	Sibley	Reed	Parsons Brinckerhoff
54	Asstephan	Sherif	Rutgers University
55	Smith	Krystal	Rutgers University
56	Wetz	Norman	Arizona Department of Transportation
57	Soden	Derek	FHWA Division

APPENDIX C. IDENTIFICATION OF BRIDGE PERFORMANCE STUDY TOPICS

Through information gleaned from a series of stakeholder interviews and literature review, a proposed series of study topics were identified. Table 20 lists these general study topics. Additional topics and refinement of the proposed topics are being considered as additional input and are gathered from stakeholders.

Table 20. LTBP suggested study topics.

Category	Study Topic
Decks	Performance of untreated concrete bridge decks
	Performance of bridge deck treatments (membranes, overlays, coatings, and sealers)
	Influence of cracking on the serviceability of high-performance concrete decks
	Performance of precast reinforced concrete deck systems
Joints	Performance, maintenance, and repair of bridge deck joints
	Performance of jointless structures
Concrete bridges	Performance of bare, coated, or sealed concrete superstructures and substructures (considering splash zone, soils, or exposed to deicer runoff)
	Performance of prestressed concrete girders (including American Association of State Highway and Traffic Officials type I girders, adjustable box girders, and bulb tees)
	Performance of embedded or ducted prestressing wires and post-tensioning tendons
Steel bridges	Performance of coatings for steel superstructure elements
	Performance of weathering steels
Bearings	Performance, maintenance, and repair of bridge bearings
Foundations and scour	Performance of structure foundation types
	Direct, reliable, and timely methods to measure scour
	Performance of scour countermeasures
Functional	Criteria for classification of functional performance
Risk and reliability	Risk and reliability evaluation for structural safety performance
Design alternatives	Performance of alternative reinforcing steels
	Performance of innovative designs and material

The LTBP team completed a cursory literature review on each of the identified study topics, providing a brief summary of the state of practice, previous related research, and identification of remaining questions that might be addressed under the LTBP program. By documenting fundamental research questions to be addressed, researchers were then able to identify the range of documentation, inspection, testing, instrumentation, and monitoring necessary to advance the state of knowledge in the topic of interest. This information can be used to identify specific data needs and specify procedures and protocols for obtaining the required or desired information.

For each study topic, a series of key questions were posed to elucidate the knowledge gaps identified and direct the development of appropriate experiments to address those questions. For each question, one or more hypotheses were posed to describe the anticipated outcomes of the experiments, and then the data required to address and evaluate each hypothesis were formulated. Such data sources include combinations of already available highway network and structure-specific inventory and condition information as well as data to be specifically generated under LTBP through field observation and testing or data mining from internal or external sources. Thus, the general study topics are to be refined into a series of experiments and specific data needs identified to support those experiments.

The goal is to establish a series of experiments and select representative samples of the bridge population for field evaluation and monitoring over the program period to gather the necessary quantitative data to answer the questions posed and refine criteria and models for bridge performance. It is desired that the information developed under this program address all aspects of performance of a typical bridge, ranging from structural condition and stability to functionality. The intent is for the information gleaned to be applicable to a broad range of structures throughout the United States and be of direct benefit to the bridge maintenance and management personnel responsible for the bridges' care.

APPENDIX D. BREAKOUT SESSION I (PERFORMANCE ISSUES)—GROUP 1

BRIDGE PERFORMANCE ISSUES

During breakout session I, group 1 identified a list of bridge performance issues related to geotechnology, which is shown in table 21. In compiling this list, group 1 noted that there are important interrelationships between some of the issues in the list. The issues were grouped according to the following general topic categories:

- a = Abutment interface.
- f = Foundations.
- h = Hydraulics.
- m = Materials.
- c = Construction.

Also, some of the issues were rated as to their level of importance in impacting overall bridge performance. The rating scale is 3 = highest importance, 2 = medium importance, and 1 = lowest importance.

Table 21. Group 1 bridge performance issues.

Category	Bridge Performance Issue	Importance
a	Bump at the end of the bridge	3
a	• Lateral spreading at abutment	3
a	• Joint filler failure	3
a	• Dynamic load amplification on ridge	3
a	• Approach slab settlement	3
a	Temperature loads on integral abutments	3
a	Integral abutment ratcheting and forces	3
a	Behavior of shallow foundations behind MSE walls	2
a	Behavior of pile foundations behind MSE walls	3
a	Effect of grade, heavy skew, or superelevation on abutments	2
a	Interaction between performance of one abutment on opposite abutment	1
f	Differential movements	1
f	Measured foundation loads to calibrate/refine design codes	3
f	• Accurate modeling during design (effects of pile caps, etc.)	3
f	• Different behavior of foundation to short-term and long-term loads	3
f	• Improved efficiency in foundation design	3
f	• Proper combination of extreme events	3
f	• Design for serviceability under lower seismic events	3
f	Unknown foundations	3
f	Effects of widening structures	3
f	• Effects on existing structures	3
f	• Use of different foundation types	3
f	Quantification of tolerable movements for design	3
f	• Vertical	3
f	• Lateral	3
h	Accurate prediction of scour	3
h	Monitoring of scour	3
h	Monitoring of scour countermeasures	3
h	Effect of laterally migrating streams	1
h	Effect of toe erosion on slope stability	2
h	Drainage performance	3
m	Long-term creep of MSE walls	2
m	Quality of fill and effect on MSE wall performance	2
m	Corrosion of MSE reinforcement	2
m	Corrosion of piles in aggressive/corrosive environments	3
m	Construction of large diameter drilled shafts	2
m	• Thermal stresses during construction (mass concrete)	2
c	QC during construction	3
c	• Effects on long-term performance of the structure	3
c	• Effect of various contract methods (design-build versus design-bid-build)	3

APPENDIX E. BREAKOUT SESSION I (PERFORMANCE ISSUES)—GROUP 2

ISSUES RELATED TO SUBSTRUCTURE AND FOUNDATIONS

The performance issues were further evaluated by considering their relative impact on strength, serviceability, survivability, and structural safety. Table 22 provides the results of this evaluation.

Table 22. Group 2 bridge performance issues with voting.

Votes	Element	Sub-Element	Performance Issue
0	General	N/A	Safety margin lower than desired, loads greater than originally designed for, or capacity reduced over time due to substructure changes
0	General	N/A	Changes in substructure stiffness over time and their impact on overall structure behavior and performance
11	Approaches	Embankments	Settlement-related impacts on serviceability (bump at the end of the bridge)
10	Approaches	Embankments	Global stability (slope failure)
2	Approaches	Embankments	Erosion/overtopping
0	Approaches	Embankments	Potholes or rutting (indicative of other issues)
0	Approaches	Embankments	Saturation of slopes and changes in shear strength over time
14	Piers	General	Scour/erosion and loss of lateral stability, compromised protection
13	Piers	General	Total and differential settlement
11	Piers	General	Horizontal movement or rotation
7	Piers	General	Loss of flexural strength of deep foundation elements due to corrosion, cracking, etc.
6	Piers	General	Vertical geotechnical bearing
3	Piers	General	Debris accumulation
0	Piers	General	Damage to foundation element caused by collision, ice flow, earthquake, or other extreme events
0	Piers	General	Cracking and corrosion of reinforcement/strand
0	Piers	General	Global stability
11	Abutments	General	Vertical and horizontal joint movement
11	Abutments	General	Total and differential settlement
8	Abutments	General	Scour/erosion
8	Abutments	General	Pile performance—corrosion, loss of flexural strength
4	Abutments	General	Slope protection performance, compromised protection
4	Abutments	General	Global stability
3	Abutments	General	Piping loss and migration of fines
2	Abutments	General	Vertical geotechnical bearing
2	Abutments	General	Drainage and filtration
1	Abutments	General	Earth retention
0	Abutments	General	Cracking
0	Abutments	General	Impact loading (dynamic due to live load)
0	Abutments	General	Collision impact (by trucks, vessels, etc.)
0	Abutments	General	Driving stresses on piles
0	Abutments	General	Abutment influence on bearing performance (protection or support)
11	Abutments	MSE walls	Corrosion/degradation of reinforcement
10	Abutments	MSE walls	Drainage failure
5	Abutments	MSE walls	Settlement
2	Abutments	MSE walls	Leakage of backfill
0	Abutments	MSE walls	Global stability
14	Abutments	Soil-nail walls	Corrosion of tendons
5	Abutments	Soil-nail walls	Horizontal movement
5	Abutments	Soil-nail walls	Drainage failure

3	Abutments	Soil-nail walls	Scour/erosion
1	Abutments	Soil-nail walls	Fascia deterioration/spalling
0	Abutments	Soil-nail walls	Cracking
0	Abutments	Soil-nail walls	Global stability due to changes in ground-water
8	Abutments	CIP walls/other	Scour/erosion
5	Abutments	CIP walls/other	Excessive displacement
1	Abutments	CIP walls/other	Corrosion
0	Abutments	CIP walls/other	Cracking
12	Abutments	Integral abutments	Soil restraint of abutment translation (jacking)

N/A = Not applicable.

APPENDIX F. BREAKOUT SESSION I (PERFORMANCE ISSUES)—GROUP 3

The approach by group 3 consisted first of brainstorming a list of performance issues to capture the complete spectrum of possible problems (see table 4). Next, in order to facilitate the evaluation of the relative importance of these issues, the full list of issues was rolled up into seven categories: movement/deflections, safety/usability, material performance, soil structure interaction, construction, recertification/reassurance, and drainage/runoff/erosion. Subcategories were developed in some cases. To evaluate the relative importance of each category, the group considered four metrics for each category or subcategory: the likelihood of the issue developing, the safety implications of the issue, the effect of the issue on bridge serviceability, and the cost of the issue. Each metric was then rated on a scale of 1 to 3 where 1 is low and 3 is high. The ratings were assigned to each metric to arrive at a score for each category or subcategory and are shown in the following sections. These ratings were used to create the summary list of performance issues (see table 4).

SHORT LIST BASED ON BRAINSTORM

Movement/Deflections

- Bump at the end of the bridge (significant).
    - Likelihood: 3.
    - Safety: 2.
    - Serviceability: 3.
    - Cost: 2 (recurring cost).
    - **Score: 21 (2nd priority).**
- Differential.
    - Likelihood: 1 (low for bread-and-butter bridges, rarely use timber piles).
    - Safety: 1 (happens slowly).
    - Serviceability: 2.
    - Cost: 3.
    - **Score: 6.**
- Lateral.
    - Likelihood: 1.
    - Safety: 1.

- Serviceability: 3.
- Cost: 3.
- **Score: 7**

Safety/Usability

- Collapse.
  - Likelihood: 1.
  - Safety: 3.
  - Serviceability: 3.
  - Cost: 3.
  - **Score: 9.**

Material Performance

- Corrosion/deterioration (MSE walls, steel in piles, and embankment material).
  - Likelihood: 3.
  - Safety: 2.
  - Serviceability: 2.
  - Cost: 3.
  - **Score: 21 (top priority).**
- New materials/new systems (lightweight fills, geofoam, composites, high-performance concrete, etc).
  - Likelihood: 1 (tends to be overly conservative with a high safety factor applied when new materials are used).
  - Safety: 1.
  - Serviceability: 1.
  - Cost: 2.
  - **Score: 4.**

Soil Structure Interaction

- Fatigue/integral abutment/lateral stress.
  - Likelihood: 3.
  - Safety: 1.
  - Serviceability: 3.
  - Cost: 3.
  - **Score: 21 (3rd priority).**

Construction

- Inadequate QA/QC, lack of records, unknown foundations (including load rating, widening, and scour issues), and known damage/material defect left in place (construction anomalies).
  - Likelihood: 3.
  - Safety: 1.
  - Serviceability: 2.
  - Cost: 2.
  - **Score: 15.**

Recertification/Reassurance

- Remaining (foundation) service life, including after any extreme event or increasing loads (reassurance).
  - Likelihood: 3.
  - Safety: 3.
  - Serviceability: 3.
  - Cost: 2.
  - **Score: 24 (treat as separate category, not in top priority grouping).**

Note that the recertification/reassurance category is an overarching performance issue and is not in the same category as the other visible or physical issues listed. It cannot be monitored in the same manner envisioned for the LTBP program and is not included in table 4.

Drainage/Runoff/Erosion

- Likelihood: 3.
- Safety: 1.
- Serviceability: 3.
- Cost: 2 (continuing maintenance).
- **Score: 18.**

Of Value to LTBP

- Examine monitoring techniques.
  - What can reliably be measured 75–100 years down the road?
  - How reliable is monitoring equipment?
- Need permanent reference marks to make periodic assessment more accurate/useful.
  - Do not necessarily need continuous monitoring.
  - Need good as-built plans to document foundation type.
- Examine new technologies to improve maintenance/construction. Periodically monitoring settlement via laser/reference marks is easy compared to identifying unknown foundations.
  - Technology not quite there yet to reliably determine unknown foundations.
  - Not trivial job.
  - More costly.
- What can be done with current technology?
  - Low-risk approach.
  - Opportunity for tremendous improvement.
  - Better utilization of current monitoring/testing technologies; not currently done.
  - Can assess in 20 years to see what difference it made.
- What are areas where new technologies could be useful going forward?
- State of the practice on approach slabs—how do various States handle it?

- Broad objectives include safety/serviceability—approach slab fits under both.
- Need to be able to tell public some movement OK, not necessarily wrong.
- Lack of guidance on how much movement various structure types can tolerate.
- Need good quick post-disaster assessment.
- Time domain reflectometry (TDR) has good potential; more known reliability.

SUMMARY

List of Priority Issues

1. Corrosion/deterioration (MSE walls, steel in piles, and embankment material).
2. Bump at the end of the bridge (significant).
3. Fatigue/integral abutment/lateral stress.
4. Drainage/runoff/erosion.

Remaining Service Life, Long-Term Performance

1. Ongoing bridge inspection.
2. Less frequent extreme event evaluation.

APPENDIX G. BREAKOUT SESSION II (DATA NEEDS)—GROUP 2

The following list indicates some types of data that are or may be currently collected depending on
agency practices:

- National Bridge Inventory structure inventory and appraisal form.
- Substructure.
    - Bent caps.
    - Columns.
    - Bearings.
    - Evidence of distress in below-grade elements.
    - Channel profiles (physical measurement).
    - Cracks measured.

Many inspections are cursory or not detailed and vary by agency and the number of bridges that inspection teams are responsible for inspecting. The following list indicates some general types of information that would be advantageous:

- Measurements wanted/needed.
- Measure the magnitude and rate of settlement at approach-bridge transition.
- Voids under approach slab.
- Vertical and lateral deformations at grade along length of bridge.
- Channels profiles.
- Quality geotechnical data.
- More than bore logs.
- Strength and compressibility data.
- Ground water table.
- Chemical properties (sulfates/chlorides/resistivity/pH).
- Expansion potential.

- Freeze-thaw classification.
- QC records from construction.
- As-built information.
- Detailed element location (vertical and horizontal).
- Climate data.
- Temperature.
- Precipitation.
- Storm runoff.
- Loads and stresses in piles and drilled shafts.
- Lateral earth pressures, swell pressures.
- Rideability index at transitions (similar to IRI).
- Vibration monitoring—ambient or forced vibration to observe changes in fundamental vibration modes.

MAPPING TO PERFORMANCE ISSUES

After identifying the data needs, group 2 worked to relate or map the data items to the performance issues that had been identified in breakout session I. This is shown in table 23, where the data items were mapped to the following performance issues:

- Approach—bump at end of bridge, integral abutments, and piles.
- Soil-structure interaction—integral abutment/lateral stress/cyclic stresses, including foundation elements.
- Foundation loads and actual capacity—impact of widening and tolerable movements.
- Unknown foundations.
- Deformation—total or differential settlement and horizontal movement.
- Joint movement—vertical and horizontal.
- Hydraulics and scour (channel migration).
- Drainage/runoff/erosion.

- Slope stability.
- Corrosion/deterioration (MSE walls, steel in piles, and embankment material).
- Quality—influence/value of quality of design, construction, and maintenance in long-term performance
- Remaining service life—long-term performance.

Table 23 also includes information on the frequency of gathering data, as well as the current availability of that data. For the column labeled “Frequency,” the following apply:

- O = Information should be obtained from the original source, such as design calculations, construction plans, construction inspection records, or as-built drawings.
- P = Data should be gathered on a periodic basis.
- C = Data should be gathered on a continuous basis.

For the column labeled “Availability,” the following apply:

- A = Information/data are currently available.
- I = Information/data are obtainable.
- F = Information/data may be available in the future.
- N = Information/data are not available and are not obtainable.

Table 23. Group 2 data needs.

Data	Frequency[1]	Availability[2]	Approach (Bump)	Soil-Structure Interaction	Foundation Loads	Unknown Foundations	Deformation	Joint Movement	Hydraulics and Scour	Drainage and Erosion	Slope Stability	Corrosion / Deterioration	Quality	Remaining Life
Magnitude and rate of settlement at approach-bridge transition	P	I	X	X	X	X	X	X		X	X	X	X	X
Voids under approach slab (change in support conditions)	P	I	X				X	X		X	X	X	X	X
Vertical and lateral deformations (surface profile changes)	P	I	X	X	X	X	X	X	X	X	X	X	X	X
Channels profiles (changes over time)	P/C	A/I/F		X	X	X	X	X	X	X	X	X	X	X
Quality geotechnical data	O	A/I	X	X	X	X	X	X	X	X	X	X	X	X
QC records from construction	O	A/I/N	X	X	X		X	X	X	X	X	X	X	X
Bridge load rating and inspection reports	O	A	X	X	X	X	X	X	X	X	X	X	X	X
Maintenance records	P	A	X		X	X	X	X	X	X	X	X	X	X
As-built information	O	A/I/N	X	X	X		X	X	X	X	X	X	X	X
Climate data (time history)	C	A/I	X	X	X	X	X	X	X	X	X	X	X	X
Loads and stresses in piles and drilled shafts and footings	P/C	I/F	X	X	X	X	X		X		X	X	X	X
Loads and stresses in superstructure elements	P/C	I/F	X	X	X	X	X		X		X	X	X	X
Lateral earth pressures, swell pressures	P	I/F	X	X	X		X	X	X	X	X	X	X	X
Rideability index at transitions (similar to IRI)	P	A/I/F	X				X	X	X	X	X		X	
Vibration characteristics of structure	P	A/I		X	X	X	X	X	X		X	X		
Physical characteristics of foundation (e.g., geophysical/ NDE data)	P	A/I/F	X	X	X	X	X	X	X		X	X	X	X
Live load history (magnitude and frequency)	C	A/I	X	X	X	X	X	X				X	X	X
Extreme event load history (flood, seismic, etc.)	P	I	X	X	X	X	X	X	X	X	X		X	X
Corrosion indicators (visual, physical, electrochemical, surrogate)	P	A/I										X	X	X

[1] O = Original, P = Periodic, and C = Continuous.
[2] A = Available, I = Is Obtainable, F = Future, and N = Not obtainable.
Note: blank cells indicate that the data item does not apply to the performance issue.

APPENDIX H. BREAKOUT SESSION II (DATA NEEDS)—GROUP 3

Table 24 matches the data needs identified by group 3 during breakout session II with the performance issues identified by the group during breakout session I.

Table 24. Group 3 data needs matched to main performance issues.

Performance Issue	Data Need
Bump	Vertical settlement at abutment Slope Vertical settlement profile with depth Changes over time Lateral movement Maintenance records Moisture info/profile in soil Increase load Freeze-thaw/heave Deterioration of geofoam/non-soil embankment materials
Corrosion	Chloride/sulfate concentrations, corrosivity Resistivity, pH Current condition (physical, MSE corrosion test strip) Moisture water Change over time/stiffness Construction records Concrete mix design Deterioration of geofoam /non-soil embankment materials Deicing usage/maintenance records
Scour/hydraulics	Scour/scour evolution Horizontal/vertical velocity/water depth Horizontal/vertical channel bed profile Movement of riprap Hydrodynamic load Changes in debris/mining
Integral abutment/soil structure interaction	Cracking/spalling Differential movement Temperature Joint closure/buckled approach sections
Drainage/runoff	Dye tracking Volume—weir Precipitation Changes in land use/vegetation Deflections on abutment, erosion Location and condition—drainage pipes/materials Presence and magnitude of voids Corrosion of exposed elements Visual observations
QA/QC	Historic records Project close-out reports Concrete sampling records Pile driving records Stiffness change issues Damage left in place Load test information

Foundation	Historic records Unknown foundation quantification Integrity after extreme event Nearby construction, changes in geometry Visible inspection, including National Bridge Inventory Measure internal forces within structure
Earth-retaining structures	Differential movement (horizontal, vertical, lateral, and rotation) Surface cracking/spalling Ground water pressures Drainage conditions, weep holes, etc. New global stability issues Gaps or cracks in soil behind wall Corrosion of wall elements Expansive soils

APPENDIX I. BREAKOUT SESSION III (TECHNOLOGY DEVELOPMENT)—GROUP 1

Table 25 presents the list of technology development needs that group 1 identified as necessary or desirable to support collection of data for the identified performance issues. The fourth column in this table, "Notes," provides commentary where appropriate on some of the tools and technology items. Blank cells indicate that no commentary was provided by the group.

Table 25. Group 1 tools, technology development, and monitoring data needs.

Data Needs	Code	Tools/Technology	Notes
Bump at the end of the bridge			
Rideability/profiler	M	Pavement surface analyzer (IRI)	Needs additional refinement
Traffic (ADT and ADTT)	A	Weigh in motion (WIM)	
Construction records, foundation report	A	Archive/existing database/ protocols (new construction)	
Weather data	A	Existing database/weather station	
Elevation survey	M	Traditional survey/laser/GPS	Further refinements to laser scanners
Bridge type/abutment	A	Archive/existing database/ protocols (new construction)	
As-built plans/details	A	Archive/existing database/ protocols (new construction)	
Post-construction instrumentation monitoring records	G/A	Existing pressure cells, strain gauges, tilt sensors, displacement transducers, etc.	Query owners for available structures
Integrity of embankment—vertical and lateral movement	M	Inclinometers, survey, point of reference measurements	Need better pressure cell technology
Integrity of foundation subsoil—vertical and lateral movement	M	Inclinometers, survey, point of reference measurements	Need better pressure cell technology
Loads on retaining walls	M/G	Load cells	Need better pressure cell technology, survivability of strain gauges
Dynamic loads on structure	M	Strain gauges (superstructure)	Embedded fiber optics
In situ and fill soil conditions	A/M	Borings/cone penetration test (CPT), etc.	Better spatial resolution (e.g., geophysics)
Soil strain signature	M/G	Fiber optics, tell tails, spider .magnets, etc.	
Abutment movements	M	Survey, tilt meters, level, plumb bob	
Water table info	M	Piezometers, geophysics	
Soil erosion and loss	M	Visual inspection, high resolution survey	
Cyclic strain (freeze-thaw/heaving)	M	Existing database/weather station	
Depth of influence of truck loads	M	Array of soil strain gauges	
Approach pavement info	A	Cores, archive/existing database/protocols (new construction)	
Approach transition detail	A	Archive/existing database/protocols (new construction)	
Maintenance records	A/G	Archive/existing database/protocols (new construction)	

Corrosion/deterioration (MSE walls, steel in piles, etc.)			
Ground water corrosivity	M	Sample and test/in situ instruments	
Soil corrosivity	M	Sample and test/in situ instruments	
Winter maintenance practice	A	Archive/existing database/ protocols (new construction)	
Stray electric currents	M	Geophysics	
Weather data	A	Existing database/weather station	
Backfill type and testing procedures	A	Archive/existing database/ additional samples	
Surface drainage (salt intrusion from poor drainage)	M	Visual inspection, moisture sensors	
Water table elevation and fluctuation	M	Piezometers, geophysics	
Corrosion and conditions of connection in MSE walls	M	Linear polarization resistance (LPR), coupons, reinforcement samples	Embedded systems
Visual indications of corrosion on wall face	A	Visual inspection	
Visual indications of corrosion on piles	A	Visual inspection/underwater inspection	
Corrosion rates	G	LPR, coupons, reinforcement samples	Geophysical
Section loss	M/G	Physical measurement	Need for tool for buried elements, geophysical
Properties of foundation element (properties, coatings on steel, etc)	A	Archive/existing database/ protocols (new construction)	
Condition of foundation element (properties, coatings on steel, etc)	M	Physical measurement, forensics	
Diffusion rate of chloride	G	Physical sampling	Embedded instrumentation, geophysics
Deterioration of timber piles	M	Visual inspection/underwater inspection/boring	
Foundations (measure loads, widening, unknown foundations, tolerable movements)			
Construction records, foundation report	A	Archive/existing database/ protocols (new construction)	
Bridge type/abutment	A	Archive/existing database/ protocols (new construction)	
As-built plans/details	A	Archive/existing database/ protocols (new construction)	
Strain distribution along element with time	G	Smartpile	Smarter piles
Foundation type/materials	A	Archive/existing database/ protocols (new construction)	
Subsurface information	A	Borings/CPT, etc.	Better spatial resolution (e.g., geophysics)
Water table elevation and fluctuation	M	Piezometers, geophysics	
Existing capacity	G	Reassessment of capacity based on existing conditions	Innovative load test methods for existing elements
Geometry	A	Archive/existing database/ protocols (new construction), coring	Geophysics
Integrity of element	G	Visual inspection, coring, geophysical	Underwater robotic inspection

Foundation stiffness and changes over time	M	Bridge load testing	
Element vertical and lateral movements	M	Inclinometers, survey, point of reference measurements, lasers, GPS	
Correlating superstructure forces/behavior/movement	M	Analysis of geotechnical and structural data	
Baseline survey data	M/G	Traditional survey/laser/GPS	Further refinements to laser scanners
Weather data	A	Existing database/weather station	
Ice thickness and properties	M	Load cells, physical measurements	
Stress/strain in MSE reinforcement	M/G	Smart reinforcements (new construction)	Strain gauges with relaxation
Measured earth pressure on wall/abutment	M/G	Load cells	Need better pressure cell technology, survivability of strain gauges
Hydraulics (scour/drainage)			
Construction records, foundation report	A	Archive/existing database/ protocols (new construction)	
Bridge type/abutment	A	Archive/existing database/ protocols (new construction)	
As-built plans/details	A	Archive/existing database/ protocols (new construction)	
Weather data	A	Existing database/weather station	
Erosion rate	M	Erosion rate testing of samples in lab	Underwater laboratory
Design scour	A/G	Design plans, calculations	
Measured scour (real time and/or post-event)	M/G	Sonar, sonic, mechanical devices, floating device, TDR, thermocouples on steel rod, divers, inspection report	Legrangian approach, smart particles
Stream velocity/flow rate	M	ADV, ADVP with pressure sensor	Smart particles
Countermeasure type and current condition	A/M	Visual inspection	
Subsurface information	A	Archive/existing database/ protocols (new construction), borings	
Changes in land use	A	Aerial photo, development plans, LIDAR	
Stream bed profiles/cross section	M	Sonar	Real-time measurement
Debris accumulation and removal	M/G	Maintenance records (protocols)	
Countermeasure maintenance records	A/G	Maintenance records (protocols)	
Channel stability and migration	M/G	Aerial photos, LIDAR	
Historical storm and flow data	A/G	Stream gauge data, existing databases	
Photo records	A/M	Camera, video	
Abrasion and impact damage	M	Visual inspection	
Drainage system and condition	M	Borescope, visual inspection, dye test, flow meter at outlet	
Ground cover and stabilization on side slopes	M	Visual inspection	
Hydraulic impacts of structure on	M	Stream gauge, aerial photos	

stream flow (hydraulic capacity)		
Water table elevation and fluctuation	M	Piezometers, geophysics
Effectiveness of stream training	M	Aerial photos
Dynamic response of bridge during flood events	M	Modal analysis
Erosion impact on global stability	M	Analysis, inclinometers, survey, aerial photos
Element vertical and lateral movements	M	Inclinometers, survey, point of reference measurements, lasers, GPS

A = Data that are generally available.
M = Data that could be collected or measured with existing technology and tools.
G = Data that could not be reasonably collected with available technology.
ADT = Average daily traffic.
ADTT = Average daily truck traffic.
ADV = Acoustic doppler velocity.
ADVP = Acoustic doppler velocity profiler.
Note: Research is already underway for many issues, and solutions may already have been found.

APPENDIX J. BREAKOUT SESSION III (TECHNOLOGY DEVELOPMENT)—GROUP 2

Appendix J provides a list of the technology development needs identified by group 2 during breakout session III. The letter "O" (i.e., obtainable) indicates that the technology exists and can be readily deployed, while the letter "F" (i.e., future) indicates that the technology is not yet available or not yet practical.

ENVIRONMENT

- Temperature probes (embedded and ambient): O.
- Rainfall/precipitation: O.
- Stream flow—velocity meters: O.
- Runoff or stream/groundwater chemistry (chloride/sulfate/pH/other contaminants): O.
- Bridge watch: O.

VISUAL/HANDS-ON INSPECTIONS

- Walk-through (evidence of substructure movements, etc.): O.
- Underwater inspections: O.
- Photographic: O.
- Improved guidelines or checklists: O.
- Video/time-lapse photo monitoring: O.
- Public involvement/reporting: O.

MOVEMENTS AT SURFACE

- Differential and relative movement sensors (linear variable differential transformer, potentiometer, capacitive sensor, strain gages, fiber optic strain/displacement sensors, accelerometers, and embedded passive sensors): O.
- LIDAR (aerial or ground-based): O.
- GPS: O.
- PSInSAR™: F.
- Road profiler: O.

- Radar: O.
- Reference points (survey targets): O.
- Automated total station (monitoring): O.
- Laser distance measurement: O.
- Aerial photography/photogrammetry: O.
- Ground-based photography/photogrammetry: O.

MOVEMENTS AT DEPTH

- Channel profile survey (longitudinal).
  - Periodic: O.
  - Real-time detection of change: F.
- Channel cross-section (transverse).
  - Periodic: O.
  - Real-time detection of change: F.
- Float-outs: O.
  - "Smart pebbles": F.
  - MEMS—deformation/tilt sensor: F.
- Horizontal and vertical inclinometers: O.
  - Periodic: O.
  - Real-time detection of change: O.
- TDR: O.
- Sliding collars: O.
- Sonar: F.
- Side-scan sonar: F.
- Settlement plates: O.
- Borehole extensometer: O.

GROUNDWATER AND RIVER LEVEL

- Water stage meter (reflected wave): O.
- Piezometers: O.
- Vibrating wire gauge: O.

MOISTURE CONTENT PROFILE

- TDR: O.
- Capacitive moisture probes: O.
- Resistive moisture probes: O.
- Nuclear gages: O.
- Soil suction probes (tensiometers): O.
- Thermal conductivity sensors: O.
- Tiny robots that measure everything: F.

HISTORICAL RECORDS

- Information management for scanned documents (design, construction, as-built, inspection, maintenance, etc.)—consistent collection, better storage, and ease of access: Working on it.
- Better documentation of design criteria (future construction) for shallow and deep foundation elements.

SUBSURFACE INFORMATION

- Crosshole sonic logging: O.
- Stresses through structural elements—active smart sensors: F.
- Geophysical (sonic) logs from geotechnical borings: F.
- Geotechnical in situ testing standard penetration test/CPT: O.
- Geophysical survey measurements: O.
- Resistivity survey: O.
- Geophysical tomography: F.

DETERIORATION RATE

- Corrosion sensors (chemical, corrosion rate, potential, resistivity): O.
- NDE technology yet to be developed—foundation material properties, flaw detection, and changes in dimension: F.
- Dynamic response (fundamental frequency/modes): O.
- Vibration monitoring: O.

ON-DEMAND MONITORING

- Embedded piezo films or piezo accelerometers: F.
- Design for inspectability or access for testing/measurement: F.
- Reliable sensors for long-term health monitoring: F.
- Better monitoring data management algorithms and software.

APPENDIX K. BREAKOUT SESSION III (TECHNOLOGY DEVELOPMENT)—GROUP 3

Appendix K includes table 26 through table 33, which list the tools, technologies, and monitoring devices needed currently and in the future to gather geotechnical data. These data were identified by group 3 during breakout session III.

Table 26. Group 3 bump at the end of the bridge: tools, technology development, and monitoring.

Currently Available	Near Future	Long Term
Ground penetrating radar	High-speed pavement profilers	Earth pressure cells
Survey	Smart pavement to capture loading	Smart soils with MEMS embedded
Inclinometer		
TDR moisture sensors		
Settlement points at depth		
Road profiler		
Airborne LIDAR		
User feedback (phone calls)		
Accident data		
Maintenance records		
Peak particle vibration monitoring		
Quality geotechnical data		
In situ geotechnical testing		
Tiltmeters		

Table 27. Group 3 corrosion/deterioration: tools, technology development, and monitoring.

Currently Available	Near Future	Long Term
Half cell potential	Optical TDR	Ground penetrating radar
Resistivity	Laser/radar interferometry monitoring of deflection	Shear/p-wave velocity (for elemental stiffness)
Sacrificial steel and inspection		Smart paint/coating (to measure stress and corrosion)
Concrete coring		Self-healing steel
Concrete chloride and sulfate concentrations		Self-healing concrete
Concrete cover measurements		Maintaining compatibility of strains in repair materials
Ultrasonics		Embedded biosensors (i.e., effervescent bacteria)

Table 28. Group 3 scour/hydraulics: tools, technology development, and monitoring.

Currently Available	Near Future	Long Term
Sonar	In-place sonar	Smart particles
Plumb bobs	Float out device attached to structure	Satellite/airborne imagery to detect scour holes
Float out device	Vibrations of pier structure	
TDR vertical and horizontal		
Sub-bottom profiler		
Ground-penetrating radar		
Flow monitoring		
Visual inspection/diver		
Embedded GPS reference points in countermeasures		

Table 29. Group 3 integral abutment/soil-structure interaction: tools, technology development, and monitoring.

Currently Available	Near Future	Long Term
Strain gauges Load cells Survey Inclinometer TDR moisture sensors Settlement points at depth Laser scanning Airborne LIDAR Maintenance records Quality geotechnical data In situ geotechnical testing Tiltmeters WIM (tied to performance data) Bridge response WIM Crack meters	Smart concrete/structure members to capture loading	Earth pressure cells Smart soils w/MEMS embedded Smart paint/coating (to measure stress and corrosion)

Table 30. Group 3 drainage/runoff: tools, technology development, and monitoring.

Currently Available	Near Future	Long Term
Rain gauges Satellite images Dye tracking Flow/weirs Visual inspection Reference stake measurements Acoustics Self potential TDR Vertical/horizontal movement Piezometer Camera inspection Use of security cameras Sediment traps Pollutant content of water "Torpedo" monitors—self-contained data loggers for water temp, pH, etc. LIDAR to detect soil loss	Monitor moisture in abutment wall	"Torpedo" type monitors—self-contained data loggers for flow

Table 31. Group 3 QA/QC: tools, technology development, and monitoring.

Currently Available	Near Future	Long Term
Construction records Reports on construction anomalies Maintenance records Temperature, pH, etc. LIDAR to detect soil loss	Spatially referenced database to house all docs/records Master database with all bridge records/data (in use by Nebraska Department of Roads) Smart compaction monitoring Construction Quality Index Thermal integrity testing of drilled shafts	QA methods that directly measure properties/performance issues of interest QA/QC methods to correlate construction work with long-term performance QA/QC capture all performance issues interested in (i.e., temperature gradients, etc.)

Table 32. Group 3 foundations: tools, technology development, and monitoring.

Currently Available	Near Future	Long Term
Strain gauges Load cells Survey Inclinometer Settlement points at depth Laser scanning Maintenance records Quality geotechnical data In situ geotechnical testing Tiltmeters Bridge response WIM Crack meters TDR cables embedded in foundation Settlement of foundation Load test data Embedded GPS reference points in foundations	Smart foundation elements Technique to measure existing load on foundation Laser/radar interferometry monitoring of deflection	Earth pressure cells (Energy piles/geothermal heating for heating of decks)

Table 33. Group 3 earth-retaining structures: tools, technology development, and monitoring.

Currently Available	Near Future	Long Term
Strain gauges Load cells Survey Inclinometer TDR moisture sensors Settlement points at depth Laser scanning Airborne LIDAR Maintenance records Quality geotechnical data In situ geotechnical testing Tiltmeters Crack meters Piezometers Inspect drains TDR cables	Smart concrete/structure members to capture loading Electro-conductivity of wall	Earth pressure cells New technique to measure water height behind wall face Smart soils Harnessing movement on bridge to capture energy to power sensors

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REFERENCE

1. Public Law 109-59. (2005). *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users*, U.S. Government Printing Office, Washington, DC.

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