Interim Report

FIELD TESTING OF INTEGRAL ABUTMENTS

Sponsored by the Project Development Division
of the Iowa Department of Transportation
and the Iowa Highway Research Board
Iowa DOT Project HR-399
CTRE Management Project 97-3

JUNE 1998

CTRE

Center for Transportation Research and Education

IOWA STATE UNIVERSITY

Iowa Department of Transportation

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its research management agreement with the Center for Transportation Research and Education.

Interim Report

Field Testing of Integral Abutments
HR-399

Prepared for the Iowa Department of Transportation and the Iowa Highway Research Board

by

R. Abendroth L. Greimann
M. Thomas C. Kirkpatrick

Department of Civil and Construction Engineering
Iowa State University
Ames, Iowa

June 1998

ABSTRACT

Integral abutment bridges are constructed without an expansion joint in the superstructure of the bridge; therefore, the bridge girders, deck, abutment diaphragms, and abutments are monolithically constructed. The abutment piles in an integral abutment bridge are vertically orientated, and they are embedded into the pile cap. When this type of a bridge experiences thermal expansion or contraction, horizontal displacements are induced at the top of the abutment piles. The flexibility of the abutment piles eliminates the need to provide an expansion joint at the inside face to the abutments. Integral abutment bridge construction has been used in Iowa and other states for many years. This research is evaluating the performance of integral abutment bridges by investigating thermally induced displacements, strains, and temperatures in two Iowa bridges. Each bridge has a skewed alignment, contains five prestressed concrete girders that support a 30-ft wide roadway for three spans, and involves a water crossing. The bridges will be monitored for about two years.

For each bridge, an instrumentation package includes measurement devices and hardware and software support systems. The measurement devices are displacement transducers, strain gages, and thermocouples. The hardware and software systems include a data-logger; multiplexers; direct-line telephone service and computer terminal modem; direct-line electrical power; lap-top computer; and an assortment of computer programs for monitoring, transmitting, and management of the data. Instrumentation has been installed on a bridge located in Guthrie County, and similar instrumentation is currently being installed on a bridge located in Story County.

Preliminary test results for the bridge located in Guthrie County have revealed that temperature changes of the bridge deck and girders induce both longitudinal and transverse displacements of the abutments and significant flexural strains in the abutment piles. For an average temperature range of 73° F for the superstructure concrete in the bridge located in Guthrie County, the change in the bridge length was about 1 1/8 in. and the maximum, strong-axis, flexural-strain range for one of the abutment piles was about 400 micro-strains, which corresponds to a stress range of about 11,600 psi.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

1.1 Background

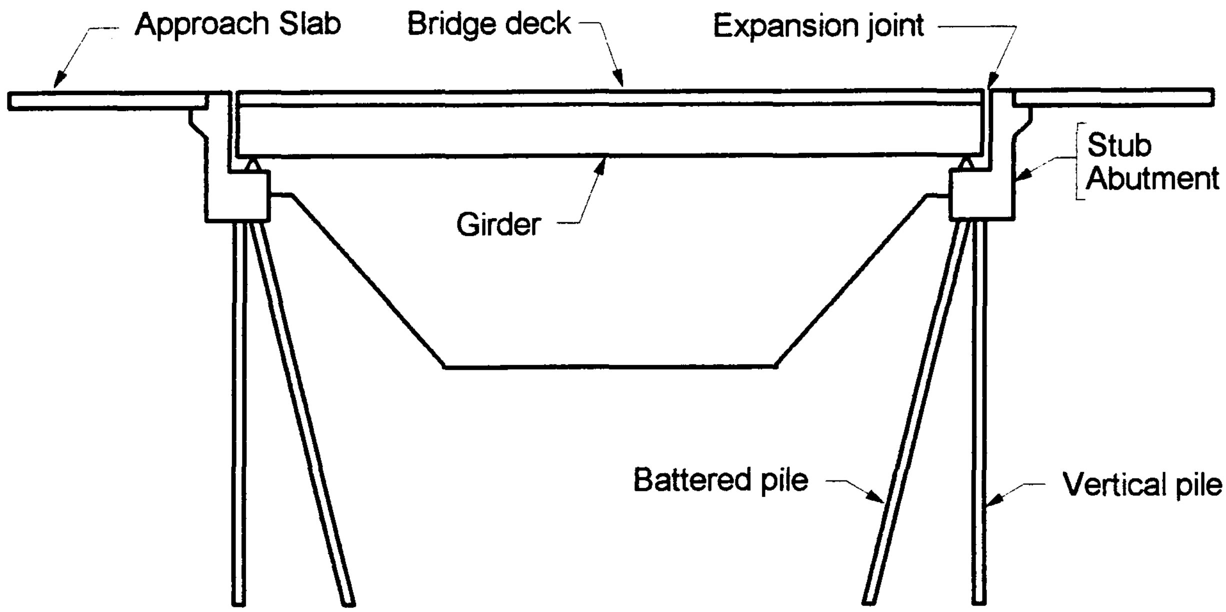
Integral abutment bridges have their abutments constructed integrally with the bridge girders and deck for the end spans, while non-integral abutment bridges have an expansion joint between the abutment and bridge superstructure. Figure 1 shows elevations of a single span integral and non-integral abutment bridge. The non-integral abutment bridge (Figure 1a) has stub abutments that are supported by vertical and battered piles, while an integral abutment bridge (Figure 1b) has abutments that are supported by only vertical piles. The lateral flexibility of the vertical piles in an integral abutment bridge permits longitudinal bridge movements that are induced by temperature changes of the bridge. To reduce the lateral resistance to horizontal displacements near the top of the piles, a pre-drilled hole that is filled with a low stiffness material surrounds each pile.

A schematic drawing of the typical geometrical arrangement of an integral abutment, wingwalls, and piles is shown in Figures 2 and 3 for precast concrete (PC) girder bridges. When an integral abutment bridge has Iowa DOT Type-A or B and sometimes Type-C, PC girders, the abutment wingwalls are cantilevered from the back side of the abutment (Figures 2a and 3a). For this abutment configuration, the piles are placed only in a single row to support the straight-wall abutment. When an integral abutment bridge has Iowa DOT Type-D and sometimes Type-C, PC girders, abutment sidewalls are constructed integrally with the abutment and an additional pile is placed directly under the end of each sidewall to help support the resulting U-shaped abutment (Figures 2b and 3b). For this abutment configuration, the wingwalls are cantilevered from the ends of the sidewalls.

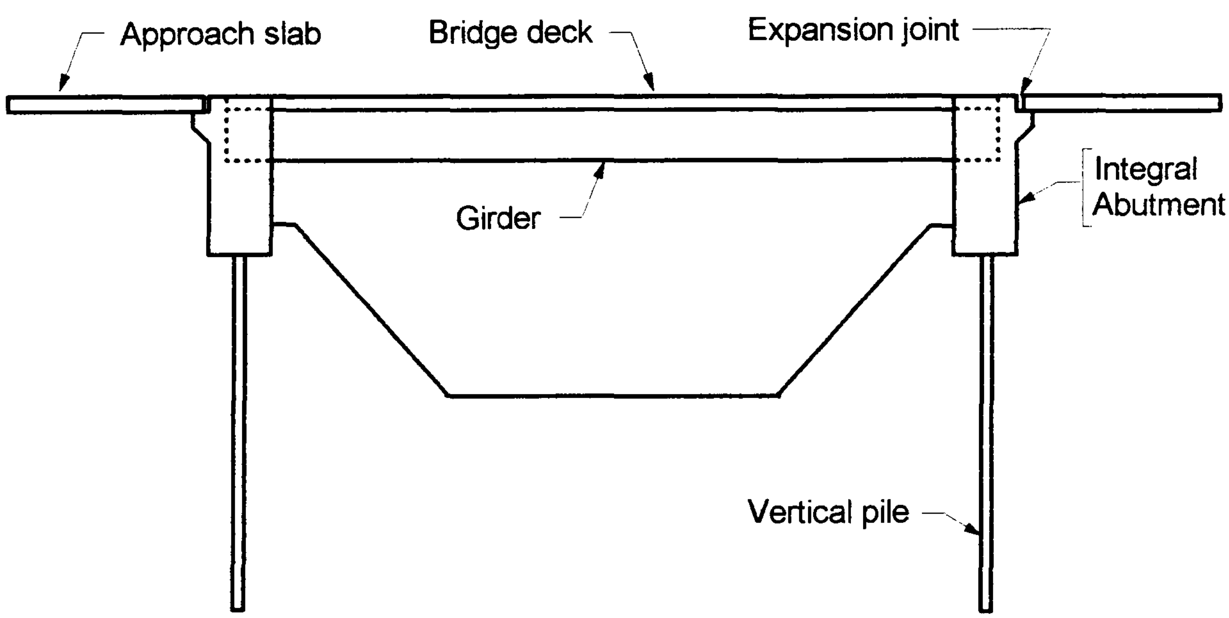
Research on integral abutment bridges was initiated at Iowa State University (ISU) in the early 1980s by Wolde-Tinsae, Greimann, and Yang[1]. Since then, several projects that were sponsored by the Iowa DOT have been conducted to evaluate the performance of jointless bridges through the use of analytical investigations involving finite-element models[2] and simple two-dimensional models[11] and by conducting laboratory tests of individual piles[6,7,8] and monitoring a single pile in each abutment of a PC girder bridge and a steel girder

---

*Superscript numbers refer to the corresponding numbers in the References.

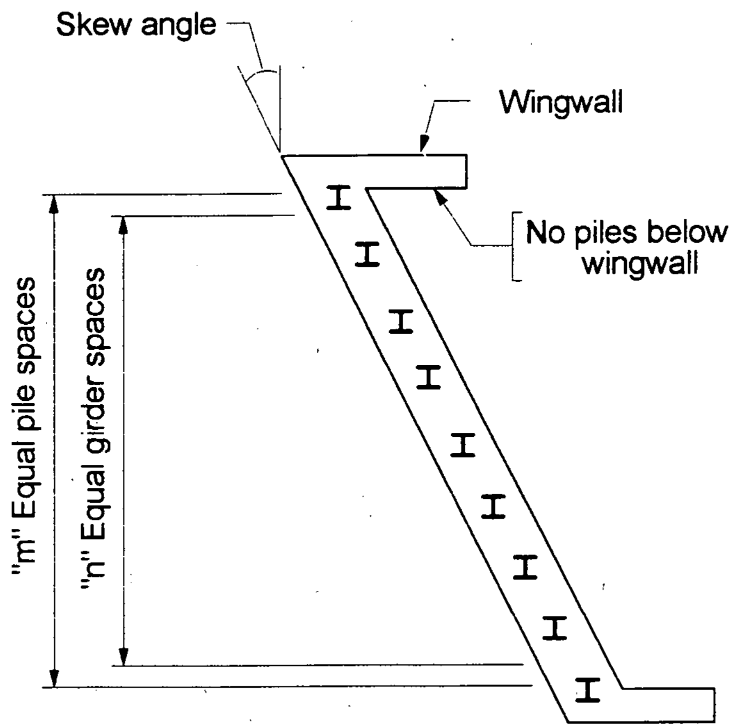


(a)

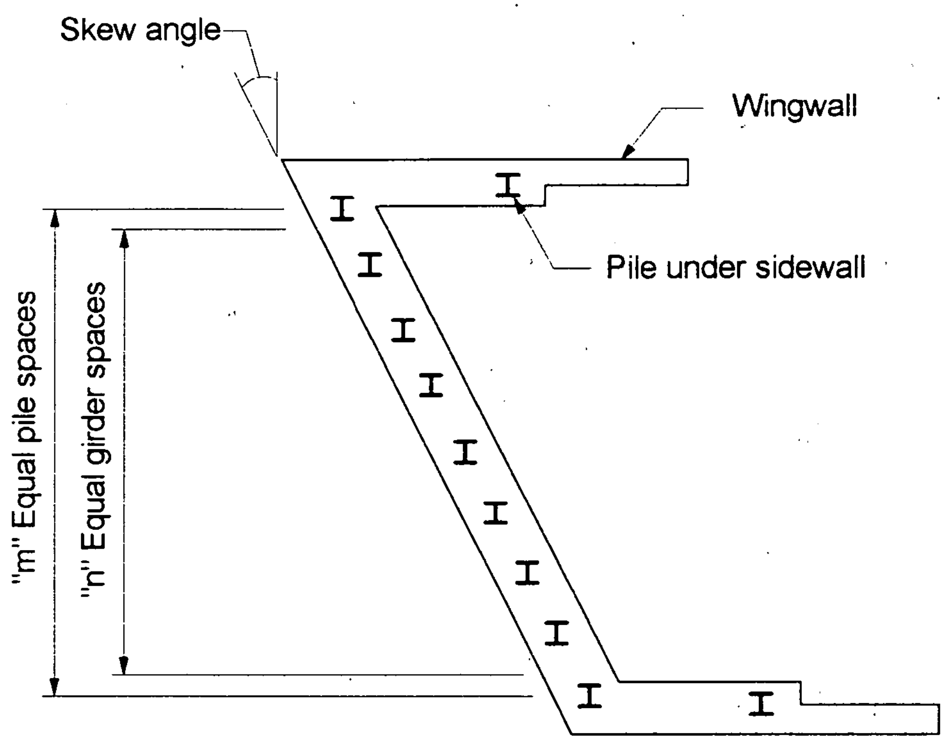


(b)

Figure 1. Bridge types: (a) Bridge with expansion joints
(b) Integral abutment bridge.



(a)



(b)

Figure 2. Integral abutment plans: (a) Iowa Type-A, B, or C PC girders, (b) Iowa Type-D PC girders.

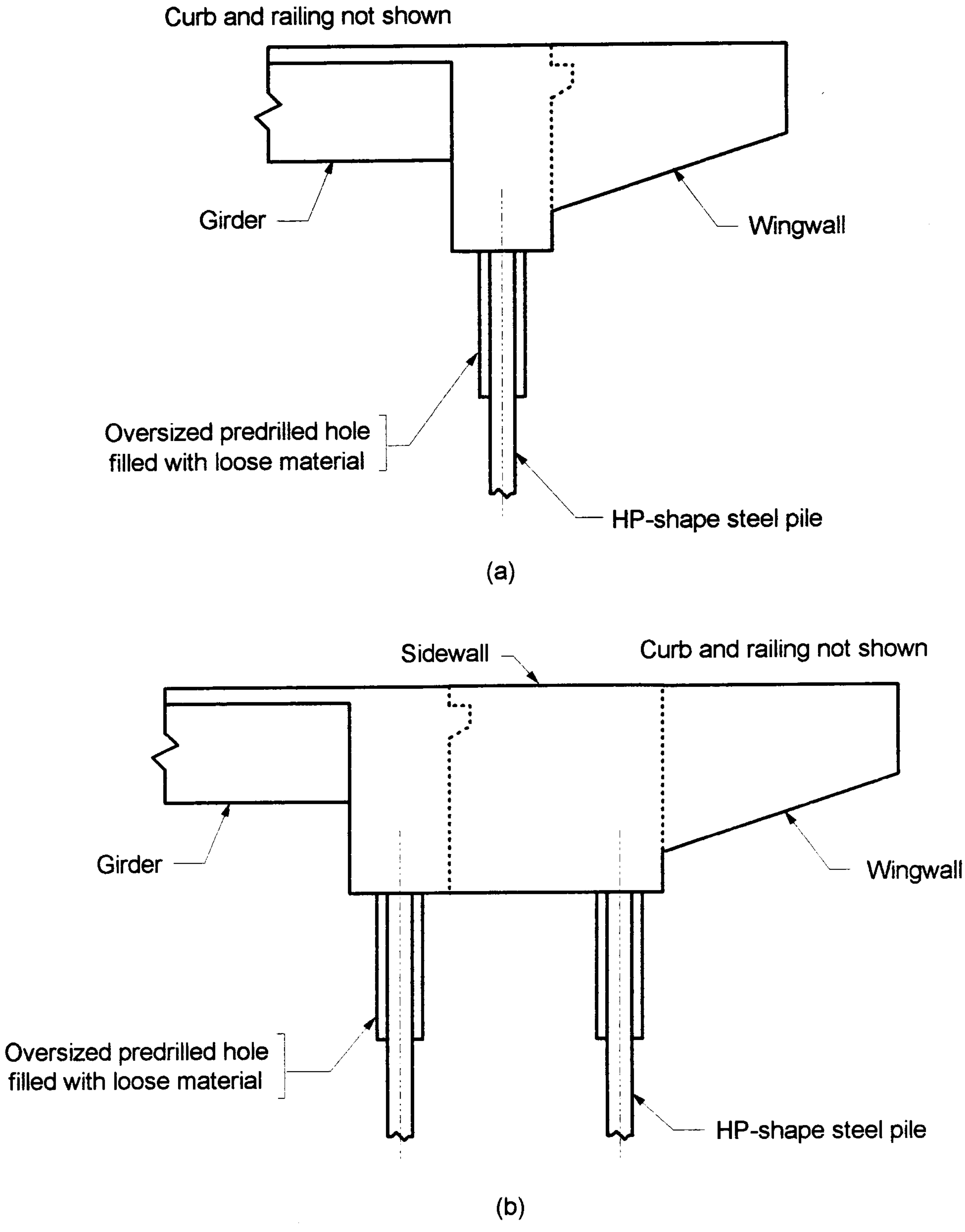


Figure 3. Integral abutment end view: (a) Iowa Type-A, B, or C PC girders, (b) Iowa Type-D PC girders.

bridge[11]. Additional information regarding the behavior of integral abutment bridges is contained in references 3, 4, and 5. This previous research led to the development of two design alternates[6,7,9,10] for the piles in integral abutments. Based on these pile design alternates, Greimann and Abendroth[10] recommended total bridge length limitations for PC and steel girder bridges with and without a skew angle. Alternate No. 1 was recommended for piles that have a limited amount of inelastic-rotation capacity (limited ductility at the locations of plastic hinge formations. Plastic hinges are induced in the abutment piles by the lateral displacements at the top of the piles caused by the thermal expansion or contraction of the bridge. Alternate No. 2 was recommended for piles that have an inelastic-rotation capacity that exceeds the inelastic-rotation demand at the plastic hinge locations. Alternate No.2 permits the design of longer integral abutment bridges than those designed by Alternate No. 1.

Full-scale pile tests were conducted by Greimann, et. al.[6] on a single pile and girder system and on an isolated single pile. The pile and girder system was subjected to vertical loads when the top of the pile was prevented from moving laterally and when the top of the pile was initially laterally displaced to represent a thermal expansion or contraction of a bridge. Another pile test was conducted with only lateral loads applied at the top of the pile. This research[6] also investigated the vertical and lateral load response of small-scale model piles with and without a rigidly connected girder.

Girton[11] conducted two bridge tests in Iowa. For each bridge, the relative longitudinal bridge expansion and contraction between the integral abutments, longitudinal strains in one pile, and temperature gradients at several locations in the bridge deck and girders were measured. The experimentally measured strains were compared to analytical predictions of these strains. The final report for this research presented comparisons of the experimentally measured and analytically predicted pile strains, summarized the two pile design alternates[10], and presented examples that applied the two pile design alternates to the bridges that Girton instrumented. His research also experimentally established the coefficient of thermal expansion and contraction of concrete that was used for the bridge abutments.

1.2 Research Objective

The objectives of the research reported here are to evaluate the state-of-the-art design philosophies for integral abutment bridges and to validate the two pile design alternates[10] that are the basis of the present integral abutment pile design procedures used by the Bridges and Structures Design Department of the Iowa DOT. To accomplish these objectives, the research effort was subdivided into the following eight research tasks: Literature Review, Bridge Selection, Instrumentation Package, Field Testing, Material Expansion and Contraction Coefficients, Field Test Evaluation, Analytical Studies, and Reports and Presentations.

2 Literature Review

Computerized search techniques are being used to review the literature on integral abutments and to obtain articles that were published since the last literature search for this topic. The researchers have had many discussions with Cathy French from the University of Minnesota regarding her current research that involves the monitoring of a non-skewed integral abutment bridge. Also, information has been obtained from Edward Hoppe from the Virginia Transportation Research Council regarding his recent research activity in this area.

3 Bridge Selection

3.1 Criteria

The bridge selection process involved an evaluation of the integral abutment bridges that have Iowa Type-B, C, or D, PC girders; a skewed alignment; and a relatively long total length. The list of bridges included those on the state highway and county systems. Since abutment geometry is influenced by the PC girder size, one bridge was to have U-shaped abutments and Iowa Type-D girders and the other bridge was to have straight-wall abutments and Iowa Type-C girders. Each bridge that was considered had advantages and disadvantages with respect to field monitoring. The advantages were a long length that would induce significant longitudinal thermal movements, large skew angle that would induce possible transverse thermal movements, symmetric geometry that would produce a symmetric responds to temperature changes, significant clearance above a river that would minimize the potential for flooding of the instrumentation devices, minimal highway traffic that would minimize the effect of bridge vibrations on the instrumentation readings, rip-rap or earth berms that would simplify the installation of benchmark posts for monitoring bridge displacements, and steel intermediate diaphragms that would allow for the passage of the instrumentation wiring. From a list of 91 bridges, two integral abutment bridges were selected, with the assistance of the Project Advisory

Team, for long-time field monitoring of displacements, longitudinal member strains, and internal concrete temperatures at specific locations. Each bridge has three spans, a skewed alignment, and involve river crossings. One bridge is located in Guthrie County, and it will be referred to as the Guthrie County Bridge. The other bridge is located in Story County, and it will be referred to as the Story County Bridge.

3.2 Guthrie County Bridge

The Guthrie County Bridge, which crosses the Middle Raccoon River, is located about 2 miles south of Panora, Iowa on County Route P28. The bridge has five Iowa Type-D, PC girders that are spaced at 7 ft on center and support a 30-ft wide roadway with a 1.58-ft wide curb and railing region along each side of the bridge on spans of 105.75, 106.50, and 105.75 ft. The U-shaped abutments and T-shaped piers are positioned on a 30^o-skew angle with respect to a line drawn perpendicular to the centerline of the roadway. The full-depth, RC, diaphragm construction at the northern pier includes a keyed construction joint between the top of the RC pier and the underside of the diaphragm. At the interface between the diaphragm and the pier, a 1 inch thick preformed expansion joint filler was used along each side of the keyed joint, and a 1/4 inch thick preformed expansion joint filler was used on the bottom of the key-ways and on the top surface of the pier cap. This pier was designated on the design drawings for the bridge to be a fixed pier. The partial-depth, RC diaphragm construction at the southern pier includes a space between the top of the RC pier and the underside of the diaphragm. This pier was designated on the design drawings to be an expansion pier. Each abutment has 12 steel HP 10 X 42 piles. The 10 piles along the abutment face are positioned in a single row with their webs orientated parallel to the abutment face. The single pile that supports an abutment sidewall is orientated with its web perpendicular to the longitudinal direction of the bridge. Each bridge pier is supported by a RC spread footing that is cut into and bears on a shale rock layer.

3.3 Story County Bridge

The Story County bridge, which crosses the Squaw Creek, is located in the northwest section of Ames, Iowa on County Route E26 (Cameron School Road). The bridge has five Iowa Type-C, PC girders that are spaced at 7 ft on center and support a 30-ft wide roadway and a 1.58-ft wide curb and railing region along each side of the bridge for spans of 64.08, 73.17, and 64.08 ft. The straight-wall abutments and pedestal-type piers are orientated at a 15^o-skew angle with respect to a line perpendicular drawn to the centerline of the roadway. For each bridge pier, the joint between the bottom of the pier diaphragm and the top of the pier is the same as that used for the Guthrie County Bridge; therefore, both piers could be classified as fixed piers. Each abutment and each pier contain 7 and 12, respectively, steel HP 10 X 42 piles that have their webs orientated parallel with the skew angle. The vertical piles in the abutments are in a single row. The piles for each pier extend upwards into the pier cap. These piles are positioned in a single row with the outer piles battered inward towards the top of the pier and interior piles are vertical.

A potential for flooding exists at this bridge site. However, since the water level of the Squaw Creek is being monitored as part of the flood abatement program for the City of Ames, Iowa, a sufficient amount of time will be available to remove most of the sensitive instrumentation devices if flooding becomes eminent. Since the bridge site is located close to Ames, the problems associated with transportation of personnel and equipment, coordination of field work, and the availability of undergraduate student assistance for a remote bridge site were eliminated.

4 Instrumentation Package

4.1 Overview

Instrumentation devices will measure horizontal displacements of both abutments; transverse displacement of one of the abutments; longitudinal strains in four piles at one surface of a RC abutment and in selected PC girders; and temperatures of the air and concrete at selected locations within the bridge superstructure. The specific locations of the instrumentation devices for the Guthrie County Bridge have been established with the assistance of the Project Advisory Team. The instrumentation for the Story County Bridge will be similar to that used on the Guthrie County Bridge.

For each bridge, an instrumentation package includes measurement devices and hardware and software support systems. The measurement devices are displacement transducers, strain gages, and thermocouples. The hardware and software systems include a data-logger; multiplexers; direct-line telephone service and computer terminal modem (Guthrie County Bridge only); direct-line electrical power; lap-top computer; and an assortment of computer programs for monitoring, transmitting, and managing the data.

4.2 Guthrie County Bridge

For the Guthrie County Bridge, 15, direct-current, string-type, displacement transducers (DCDTs) were used to measure longitudinal and transverse displacements and rotations at the selected locations. The DCDTs that measure the longitudinal and transverse displacements of the bridge abutments are attached to steel posts, which are located about 10 ft from the nearest vertical face of an abutment. These posts serve as bench marks for horizontal displacements. At the south pier, a DCDT measures the relative longitudinal movement between the pier and the bridge superstructure at the center girder location. Another DCDT will be installed at a similar location at the north pier. DCDTs are also being used to measure the relative rotation between the center PC girder and the south abutment diaphragm and between an interior abutment pile and the underside of the abutment pile cap.

For the Guthrie County Bridge, 63 electrical-resistance strain gages were used to measure strains in five steel HP-shaped abutment piles, five PC girders, and the north face of the south abutment. Four weldable-type, strain gages were attached on the outside face of the flanges at two cross sections for each of the monitored abutment piles to establish the axial, weak and strong-axis bending, and longitudinal torsional strains. A bondable-type, strain gage was mounted on one face of each flange of the selected PC girders to obtain the axial and strong-axis bending strains. Five bondable-type, strain gages were attached to the north face of the south abutment to detect potential curvature in the horizontal plane of the abutment pile cap.

For the Guthrie County Bridge, 54 thermocouples were used to monitor internal temperatures for the RC slab and PC girders and of the air at selected locations. At eight locations, four thermocouples measure the concrete temperature in the middle of the slab depth and in the face of the top flange, web, and bottom flange of a PC girder. Forty-eight thermocouples were used to allow for temperature correction of strain measurements. These thermocouples were placed in the flange faces of PC girders, in the north face of the south abutment pile cap, and adjacent to steel piles to measure concrete and air temperatures at the location of the strain gages. To allow for temperature correction of the displacement measurements, six thermocouples have been placed within the plywood enclosures that protect the DCDTs to measure the air temperature within the enclosures.

4.3 Story County Bridge

The DCDT, strain gage, and thermocouple devices for the Story County Bridge are being installed. The instrumentation devices and installation locations will be similar to that used for the Guthrie County Bridge.

5 Field Testing

An extensive experimental testing program is being conducted for two integral abutment bridges. Abutment displacements; abutment pile, abutment pile cap, and PC girder strains; and temperatures will be monitored two or three times per hour for about two years. This research is a significant extension of Girton's research[11].

5.1 Guthrie County Bridge

The instrumentation system has been in place at the Guthrie County Bridge since about December of 1997. Periodically, some changes, adjustments, and additions have been made to the system to produce more accurate results. A vast amount of information is being collected regarding the displacement, strains, and temperatures. This data is being managed by a computer software program and the results are being analyzed. The project proposal had specified that the bridges would be monitored through July of 1999; however, due to unavoidable delays that have been experienced, the completion date for the field testing of this bridge has been extended through November of 1999.

5.2 Story County Bridge

The instrumentation system for the Story County Bridge is being installed. This work is anticipated to be completed in July of 1998. Data for this bridge will also be collected through November of 1999.

6 Material Expansion and Contraction Coefficients

Concrete core samples are being obtained from bridge decks in several geographical locations in Iowa. These samples should contain specific aggregates that are common in those parts of the state. Also, concrete samples will be obtained from two precast concrete producers who manufacture PC girders for bridges in the State of Iowa. Using these concrete samples, laboratory tests will be conducted to determine the coefficient of thermal expansion and contraction. For the two bridges that were investigated by Girton[11], he determined that significant variation exists in the coefficient of thermal expansion and contraction for the concrete.

6.1 Specimen Preparation

Initially, 4 inch diameter concrete cores are being obtained from bridge decks and precast concrete producers. These concrete samples are being reduced to about a 3 inch diameter to form the specimens that will be used in the laboratory tests for establishing the coefficient of thermal expansion and contraction, α-coefficient, of the concrete.

6.2 Test Procedures

Test protocols have been developed, using the American Society for Testing Materials (ASTM) Standards[13] and the United States Bureau of Reclamation (USBR) Standards[14] as guides, for determining the length and α-coefficient of the specimens, respectively. Laboratory tests are being conducted for 100% dry and 100% saturated moisture conditions. Specimen length measurements will be made at temperature levels of approximately 190, 140, 70, and 40° F for the dry specimens and at temperature levels of approximately 110, 70, and 40° F for the saturated specimens.

7 Field Test Evaluation

For the Guthrie County Bridge, data reduction studies have been performed to obtain valid temperature, displacement, and strain results. These results of bridge response due to temperature variations throughout the testing period will be graphically presented. Girton[11] determined that the temperature ranges experienced by the bridge superstructures were different from those specified in the American Association of State Highway and Transportation Officials (AASHTO) Specifications[12].

8 Analytical Studies

Analytical models of each bridge will be developed and evaluated so that they can be used to predict the displacement behavior of an integral abutment bridge that is subjected to temperature changes. These models will be used to investigate the stress conditions for the abutment system that consists of the end portions of the PC girders, abutment, and piles. The two abutment pile design alternates[10] and the analytical model that were summarized by Girton[11] will be evaluated after the field tests of the bridges have been conducted and after the thermal expansion characteristics have been established.

Finite-element sub-models for an abutment pile and for an abutment assembly are being developed. These sub-models will include pile and soil interaction and abutment and soil interaction that are represented by horizontal and vertical springs. These sub-models will be incorporated into a finite-element model for the entire bridge structure. Mathematical models will be developed for the Guthrie County Bridge and for the Story County Bridge. These models will be used to predict the temperature induced longitudinal and transverse displacements of the abutments and the strains in the abutment piles and PC girders. These predicted displacement and strains will be compared with the responses obtained from the field monitoring of the two integral abutment bridges.

9 Preliminary Results

Initial analysis of the field measurements for the Guthrie County Bridge has produced preliminary results for temperatures of the bridge superstructure and for the pile strains and abutment displacements that were induced by temperature changes that occurred between December 17, 1997 and March 28, 1998.

9.1 Temperatures

The temperature distribution that occurs in a bridge superstructure is extremely complex. Temperature variations occur along the length, across the width, and throughout the thickness of the bridge deck and along the length, across the width, and throughout the depth of the PC girders. The thermocouples that have been installed in the Guthrie County Bridge are confirming that a uniform temperature does not exist in the structure. To simplify the analysis of the temperature induced abutment displacements and pile strains, an average bridge temperature will be used. The average bridge temperature is defined as the mathematical average of the measured temperatures obtained from the thermocouples in the bridge deck and PC girders. Figure 4 shows a graph of the average bridge temperature verses time. To date, the coldest and warmest average bridge temperatures of -2° F and 71° F, respectively, occurred in March of 1998; therefore, for this reporting period, the range in the average bridge temperature was 73° F.

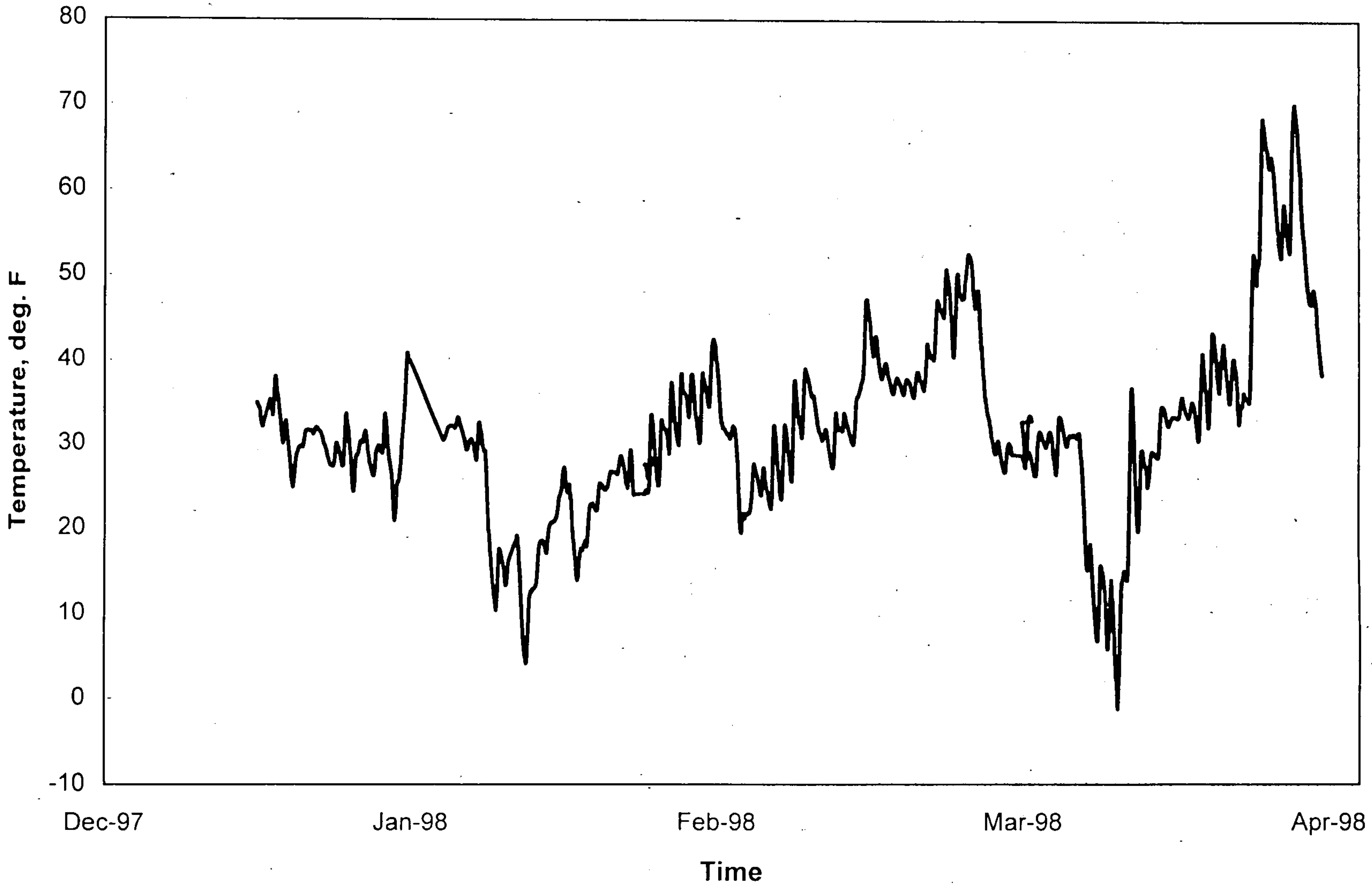


Figure 4. Average superstructure temperature for the Guthrie County bridge.

9.2 Abutment Displacements

For the Guthrie County Bridge, an investigation of the displacement results revealed that temperature changes produce both longitudinal and transverse movements of the bridge abutments. As anticipated, the longitudinal displacements are about an order of magnitude larger than the transverse displacements. Even though the south pier construction details indicated that this pier was an expansion pier and the north pier was a fixed pier, larger movements occurred at the north abutment than at the south abutment. The appearance of the graphs (not shown) of these displacements verses time, over which temperature changes occur, are very similar to the appearance of the graph for the average bridge temperature. The relative longitudinal displacement between the abutments that was measured at the location of the center PC girder is defined as the change in the bridge length. For the three-month reporting period, the change in the bridge length was about 1 1/8 inches. For a three-day period between March 12, and March 15, 1998, a graph of the change in the bridge length and a graph of the air temperature within a metal box that is attached to the underside of the bridge deck is shown in Figure 5. A comparison of these graphs illustrates that a time lag exists between a change in the air temperature and the resulting change in the length of the bridge.

9.3 Pile Strains

The measured longitudinal pile stains for the Guthrie County Bridge have revealed that the axial strain and warpage normal strains in the piles are small compared to the strong and weak-axis bending strains. Therefore, when temperature changes cause bridge expansion or contraction, predominately flexural strains and corresponding flexural stresses are induced in the piles. The graphs (not shown) of the strong and weak-axis bending strains indicate that the appearance of the variation in these strains with time, as influenced by temperature changes, are essentially identical with the appearance of the variation in the bridge length with time, as influenced by temperature changes. For the three-month reporting period, the maximum, strong-axis, flexural-strain range for the north and south abutment interior pile that is closest to the center PC girder was about 400 and 350 micro-strains, respectively, at a distance of 9 in. below the abutment pile cap. This temperature induced strain range corresponds to a temperature induced stress range of about 11,600 and 10,200 psi, respectively, which are well below the yield stress for A36 steel.

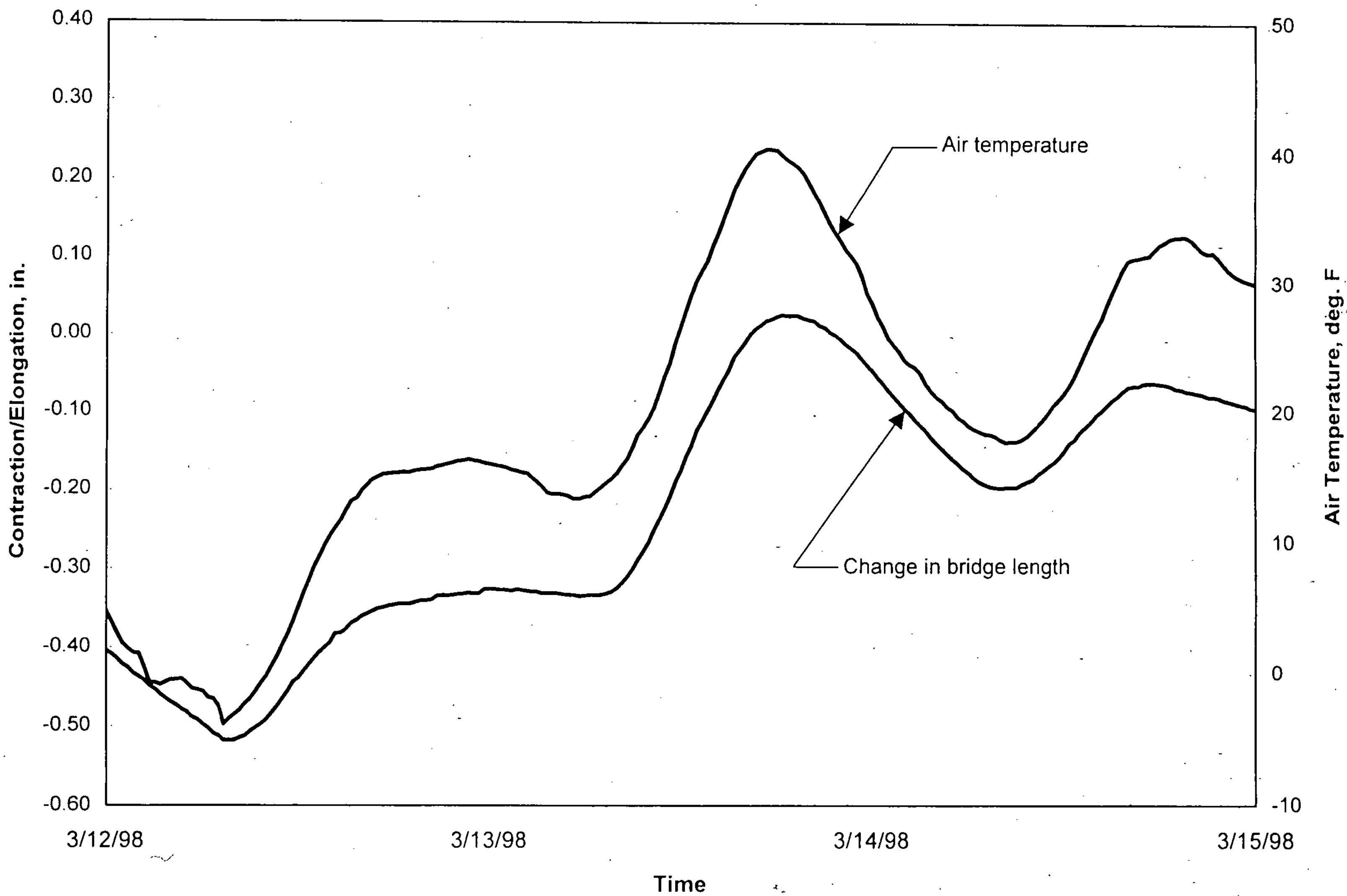


Figure 5. Change in length over a 3-day period in March for the Guthrie County bridge.

10 Acknowledgments

The Iowa DOT Research Project HR-399 presented in this report was sponsored by the Iowa Highway Division of the Iowa Department of Transportation and the Iowa Highway Research Board. The authors want to express their sincere appreciation to the former project manager, William Lundquist - former Bridge Engineer for the Iowa DOT, for his assistance and support with this project. The authors want to also thank the members of the Project Advisory Team: John Harkin - former engineer with the Iowa DOT; Mark Nahra - Cedar County Engineer; Fouad Daoud - engineer with WHKS & Company, Mason City, Iowa; and Mike Klapp - engineer with the City of Des Moines, Iowa, for their contributions to this research project. The authors extend their gratitude to Steve Akes - Guthrie County Engineer and Harold Jensen - Story County Engineer for their assistance with the work being performed on the integral abutment bridges in their counties. The authors also want to thank Kevin Jones from the Iowa DOT Maintenance Office for his help with obtaining the concrete core samples from bridge decks. A special thank you is extended to Bruce Brakke and William Stabler also from the Iowa DOT Maintenance Office for their help with providing and operating, respectively, the Iowa DOT vehicle (snooper) that provided access to the underside of the bridge deck for the installation of the instrumentation devices at the Guthrie County Bridge. The authors are also very thankful for the technical advise and assistance from Douglas Wood - Manager, Engineering Research Labs, ISU, with regards to the design and installation of the instrumentation systems. The authors are also very appreciative for the technical advice and assistance from Scott Schlorholtz - Associate Scientist, ISU, regarding the testing of the concrete cores for determining the coefficient of thermal expansion and contraction. The authors wish to provide a general acknowledgment to the many ISU undergraduate and graduate students who assisted with the preparation and installation of the instrumentation devices on the Guthrie and Story County Bridges.

11 REFERENCES

1. Wolde-Tinsae, A. M., Greimann. L. F., and Yang, P.-S., "Nonlinear Pile Behavior in Integral Abutment Bridges", *Final Report*, Iowa DOT Project HR-227, ISU-ERI-Ames 82123, February 1982

2. Yang, P.-S., Wolde-Tinsae, A. M., and Greimann, L. F., "Nonlinear Finite Element Study of Piles in Integral Abutment Bridges", *Final Report*, Iowa DOT Project HR-227, ISU-ERI-Ames 83068, September 1982.

3. Greimann, L. F., Wolde-Tinsae, A. E., and Yang, P.-S., "Skewed Bridges with Integral Abutments, *Transportation Research Record 903*, Transportation Board, National Academy of Science, Washington, D.C., 1983.

4. Wolde-Tinsae, A. M., Greimann, L. F., and Johnson, B. V., "Performance of Integral Bridge Abutments", *Journal of the International Association for Bridge and Structural Engineering*, IASBSE Proceedings P-58/83 (February 1983) 17-34.

5. Greimann, L. F., Yang, P.-S., Edmunds, S. K., and Wolde-Tinsae, A. M., "Design of Piles for Integral Abutment Bridges", *Final Report*, Iowa DOT Project HR-252, ISU-ERI-Ames 84286, August 1984.

6. Greimann, L. F., Abendroth, R. E., Johnson, D. E., and Ebner, P. B., "Pile Design and Tests for Integral Abutment Bridges", *Final Report*, Iowa DOT Project HR-273, ISU-ERI-Ames 88060, December 1987.

7. Greimann, L. F., Abendroth, R. E., Johnson, D. E., and Ebner, P. B., Addendum to: "Pile Design and Tests for Integral Abutment Bridges", *Final Report*, Iowa DOT Project HR-273, ISU-ERI-Ames 88060, December 1987.

8. Abendroth, R. E. and Greimann, L. F., "Pile Behavior Established from Model Tests", *Journal of Geotechnical Engineering*, American Association of Civil Engineers, Geotechnical Division, Vol. 116, No. 4, April 1990, pp. 571-588.

9. Abendroth, R. E. and Greimann, L. F., "A Rational Design Approach for Integral Abutment Bridge Piles", *Transportation Research Record 1223*, Bridge Design and Performance and Composite Materials, Transportation Research Board, National Research Council, 1989, pp. 12-23.

10. Abendroth, R. E. and Greimann, L. F., "Abutment Pile Design for Jointless Bridges", *Journal of Structural Engineering*, American Society of Civil Engineers, Structural Division, Vol. 115, No. 11, November 1989, pp. 2914-2929.

11. Girton, D. D., Hawkinson, T. R., and Greimann, L. F., with Bergenson, K., Ndon, U., and Abendroth, R. E., "Validation of Design Recommendations for Integral Abutment Piles", *Final Report*, Iowa DOT Project HR-292, ISU-ERI-Ames 89329, September 1989.

12. American Association of State Highway and Transportation Officials (AASHTO), *Standard Specifications for Highway Bridges*, 13th Ed., Washington, D.C., 1989.

13. American Society for Testing Materials (ASTM), *Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Monolithic Surfaces, and Polymer Concretes - ASTM C 531-95*, pp. 353 - 355, Philadelphia, Pennsylvania, 1995.

14. United States Department of the Interior - Bureau of Reclamation (USBR), Concrete and Structural Branch, Code D-3730, Research Laboratory Services Division, *Procedure for Coefficient of Linear Thermal Expansion of Concrete - USBR 4910-92*, Denver, Colorado, pp. 695 - 699, 1992.