NCHRP

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

REPORT 473

Recommended Specifications for Large-Span Culverts

TRANSPORTATION RESEARCH BOARD

NATIONAL RESEARCH COUNCIL

TRANSPORTATION RESEARCH BOARD EXECUTIVE COMMITTEE 2002 (Membership as of January 2002)

OFFICERS

Chair: *E. Dean Carlson, Secretary of Transportation, Kansas DOT*
Vice Chair: *Genevieve Giuliano, Professor, School of Policy, Planning, and Development, University of Southern California, Los Angeles*
Executive Director: *Robert E. Skinner, Jr., Transportation Research Board*

MEMBERS

WILLIAM D. ANKNER, *Director, Rhode Island DOT*
THOMAS F. BARRY, JR., *Secretary of Transportation, Florida DOT*
MICHAEL W. BEHRENS, *Executive Director, Texas DOT*
JACK E. BUFFINGTON, *Associate Director and Research Professor, Mack-Blackwell National Rural Transportation Study Center, University of Arkansas*
SARAH C. CAMPBELL, *President, TransManagement, Inc., Washington, DC*
JOANNE F. CASEY, *President, Intermodal Association of North America*
JAMES C. CODELL III, *Secretary, Kentucky Transportation Cabinet*
JOHN L. CRAIG, *Director, Nebraska Department of Roads*
ROBERT A. FROSCH, *Senior Research Fellow, John F. Kennedy School of Government, Harvard University*
SUSAN HANSON, *Landry University Professor of Geography, Graduate School of Geography, Clark University*
LESTER A. HOEL, *L. A. Lacy Distinguished Professor, Department of Civil Engineering, University of Virginia*
RONALD F. KIRBY, *Director of Transportation Planning, Metropolitan Washington Council of Governments*
H. THOMAS KORNEGAY, *Executive Director, Port of Houston Authority*
BRADLEY L. MALLORY, *Secretary of Transportation, Pennsylvania DOT*
MICHAEL D. MEYER, *Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology*
JEFF P. MORALES, *Director of Transportation, California DOT*
DAVID PLAVIN, *President, Airports Council International, Washington, DC*
JOHN REBENSDORF, *Vice President, Network and Service Planning, Union Pacific Railroad Co., Omaha, NE*
CATHERINE L. ROSS, *Executive Director, Georgia Regional Transportation Agency*
JOHN M. SAMUELS, *Senior Vice President-Operations Planning & Support, Norfolk Southern Corporation, Norfolk, VA*
PAUL P. SKOUTELAS, *CEO, Port Authority of Allegheny County, Pittsburgh, PA*
MICHAEL S. TOWNES, *Executive Director, Transportation District Commission of Hampton Roads, Hampton, VA*
MARTIN WACHS, *Director, Institute of Transportation Studies, University of California at Berkeley*
MICHAEL W. WICKHAM, *Chairman and CEO, Roadway Express, Inc., Akron, OH*
M. GORDON WOLMAN, *Professor of Geography and Environmental Engineering, The Johns Hopkins University*

MIKE ACOTT, *President, National Asphalt Pavement Association* (ex officio)
JOSEPH M. CLAPP, *Federal Motor Carrier Safety Administrator, U.S.DOT* (ex officio)
SUSAN M. COUGHLIN, *Director and COO, The American Trucking Associations Foundation, Inc.* (ex officio)
JENNIFER L. DORN, *Federal Transit Administrator, U.S.DOT* (ex officio)
ELLEN G. ENGLEMAN, *Research and Special Programs Administrator, U.S.DOT* (ex officio)
ROBERT B. FLOWERS (Lt. Gen., U.S. Army), *Chief of Engineers and Commander, U.S. Army Corps of Engineers* (ex officio)
HAROLD K. FORSEN, *Foreign Secretary, National Academy of Engineering* (ex officio)
JANE F. GARVEY, *Federal Aviation Administrator, U.S.DOT* (ex officio)
THOMAS J. GROSS, *Deputy Assistant Secretary, Office of Transportation Technologies, U.S. Department of Energy* (ex officio)
EDWARD R. HAMBERGER, *President and CEO, Association of American Railroads* (ex officio)
JOHN C. HORSLEY, *Executive Director, American Association of State Highway and Transportation Officials* (ex officio)
MICHAEL P. JACKSON, *Deputy Secretary of Transportation, U.S.DOT* (ex officio)
JAMES M. LOY (Adm., U.S. Coast Guard), *Commandant, U.S. Coast Guard* (ex officio)
WILLIAM W. MILLAR, *President, American Public Transportation Association* (ex officio)
MARGO T. OGE, *Director, Office of Transportation and Air Quality, U.S. Environmental Protection Agency* (ex officio)
MARY E. PETERS, *Federal Highway Administrator, U.S.DOT* (ex officio)
VALENTIN J. RIVA, *President and CEO, American Concrete Pavement Association* (ex officio)
JEFFREY W. RUNGE, *National Highway Traffic Safety Administrator, U.S.DOT* (ex officio)
JON A. RUTTER, *Federal Railroad Administrator, U.S.DOT* (ex officio)
WILLIAM G. SCHUBERT, *Maritime Administrator, U.S.DOT* (ex officio)
ASHISH K. SEN, *Director, Bureau of Transportation Statistics, U.S.DOT* (ex officio)
ROBERT A. VENEZIA, *Earth Sciences Applications Specialist, National Aeronautics and Space Administration* (ex officio)

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Transportation Research Board Executive Committee Subcommittee for NCHRP

E. DEAN CARLSON, *Kansas DOT* (Chair)
GENEVIEVE GIULIANO, *University of Southern California, Los Angeles*
LESTER A. HOEL, *University of Virginia*
JOHN C. HORSLEY, *American Association of State Highway and Transportation Officials*
MARY E. PETERS, *Federal Highway Administration*
JOHN M. SAMUELS, *Norfolk Southern Corporation, Norfolk, VA*
ROBERT E. SKINNER, JR., *Transportation Research Board*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 473

Recommended Specifications for Large-Span Culverts

T. J. McGrath
Simpson Gumpertz & Heger, Inc.
Arlington, MA

I. D. Moore
Queens University
Kingston, Ontario, Canada

E. T. Selig
Ernest T. Selig, Inc.
Hadley, MA

M. C. Webb
Soil Structure Interaction Specialists
Pretoria, South Africa

B. Taleb
Acres International
Niagara Falls, Ontario, Canada

Subject Areas
Bridges, Other Structures, and Hydraulics and Hydrology

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD — NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. — 2002

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

Note: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

NCHRP REPORT 473

Project C12-45 FY'96

ISSN 0077-5614

ISBN 0-309-06757-X

Library of Congress Control Number 2002106859

Price $21.00

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

and can be ordered through the Internet at:

http://www.trb.org/trb/bookstore

Printed in the United States of America

FOREWORD

By David B. Beal
Staff Officer
Transportation Research Board

This report contains the findings of a study to develop recommended design and construction specifications for metal and concrete large-span culverts. The report describes the research effort leading to the recommended specifications and includes information on field-testing and computer modeling. The methodology used to develop simplified design equations is also included. The material in this report will be of immediate interest to specification writers and to engineers concerned with the design and construction of large-span culverts.

Flexible and rigid large-span culverts, typically ranging from 3 to 9 m (10 to 30 ft), are often a practical structure for crossings, especially on local road systems. The use of these structures is growing, and the available design and construction specifications related to them are in need of improvement. Large-span culverts are complex structures whose design and performance are related to the interaction of the structure and the surrounding soil. Properties of the backfill envelope as well as in situ material have a major effect on the performance of these structures, and additional knowledge about these effects is needed.

Under NCHRP Project 12-45, Simpson Gumpertz & Heger, Inc., in cooperation with the University of Massachusetts and the University of Western Ontario, monitored the performance of full-scale metal and concrete culverts during backfilling and under vehicle loads. The results of the experimental program were modeled and extended with finite element analysis to create the data necessary to develop the simplified design expressions. The analysis and compilation of prior experience with long-span culverts provided the basis for the recommended design and construction specifications for large-span culverts. These specifications are consistent in philosophy and format with the AASHTO *LRFD Bridge Design Specifications* and are accompanied by a commentary.

CONTENTS

COOPERATIVE RESEARCH PROGRAMS STAFF FOR NCHRP REPORT 473

ROBERT J. REILLY, *Director, Cooperative Research Programs*
CRAWFORD JENCKS, *NCHRP Manager*
DAVID B. BEAL, *Senior Program Officer*
EILEEN P. DELANEY, *Managing Editor*
HILARY FREER, *Associate Editor II*
ANDREA BRIERE, *Associate Editor*

NCHRP PROJECT 12-45 PANEL
Field of Design—Area of Bridges

SUDHAKAR R. KULKARNI, *Michigan DOT* (Chair)
NANCY McMULLIN BOBB, *Federal Highway Administration*
RICHARD S. FOUNTAIN, *Sandford, NC*
MICHAEL G. KATONA, *Washington State University*
SAMUEL C. MUSSER, *Utah DOT*
GARY D. PETERSON, *Minnesota DOT*
THOMAS C. SANDFORD, *University of Maine*
JOHN O'FALLON, *FHWA Liaison Representative*
DANIEL W. DEARASAUGH, JR., (Retired), *TRB Liaison Representative*

AUTHOR ACKNOWLEDGMENTS

This report was a collaborative effort of three research agencies: Simpson Gumpertz & Heger, Inc.; the University of Massachusetts; and the University of Western Ontario. Successful completion of the project required input and assistance from many more people other than the authors.

BEBO of America Inc. and Contech Construction Products Inc. donated the test structures and delivered them to the test site without cost to the project. Delta Materials Corp. provided a site for conducting the tests, also without cost to the project.

Prof. James LaFave, Jeanne Sussmann, Raymond Frenkel, Daniel Lovett, Troy Thiele, Brian Rowley, and Jun Wang made significant contributions to the field tests.

Khaled El Sawy completed much of the pretest computer modeling.

Stephen DelloRusso and Daniel Valentine worked on instrumentation issues and evaluation of the simplified design methods.

RECOMMENDED SPECIFICATIONS FOR LARGE-SPAN CULVERTS

SUMMARY

This project has completed a thorough review and evaluation of the state of the art in design and construction of large-span reinforced concrete and metal culverts, investigated culvert behavior through full-scale field tests and extensive computer modeling, and developed recommended specifications for design and construction.

This review indicates that current practice produces safe, reliable structures; however, much of the success is believed to result from experience, as current design procedures are not specific and leave many important structural details unspecified. In particular, current procedures for metal culverts are largely empirical and do not address several key aspects of design, such as the role of stiffeners or the evaluation of moments that develop during construction or in shallow-buried structures subject to live load. Current practice for concrete culverts is more defined than for metal culverts, but some key areas are still not addressed, such as the vertical load to be used in design. The review also demonstrated the importance of following correct construction procedures, as a number of failures of large-span culverts have been attributed to poor control during construction. There is a definite need for AASHTO to implement improved specifications.

The key focus of the project was to develop new design models for large-span culverts: (1) a simplified procedure that would accurately model most culvert installations and be suitable for incorporation into AASHTO specifications, and (2) a comprehensive procedure that could be used for unusual installation or design conditions. The method used to develop these procedures was as follows:

- Full-scale field tests to develop data on culvert behavior during construction and under shallow fills subject to live loads,
- Calibration of computer models with the field data,
- Parametric studies of culvert behavior with calibrated computer models,
- Development of simplified design equations based on parametric study results, and
- Calibration and adjustment of the simplified design method through application of the simplified design procedures for a range of culvert types and sizes.

The full-scale field tests evaluated the performance of a 9.5-m (31.2-ft) span metal arch culvert and a 9.1-m (30-ft) span precast, reinforced concrete arch culvert. The

metal arch construction deviated from current practice in that it was constructed without longitudinal or circumferential stiffeners as required by current practice. The concrete arch culvert was designed in accordance with the manufacturer's standard procedures. The arches were installed on cast-in-place footings and embedded in granular backfill. Live-load testing was conducted with a truck with 310 kN (70,000 lb) on tandem axles at depths of 0.9, 0.6, and 0.3 m (3, 2, and 1 ft). Both structures performed well during the testing. At the minimum depth of fill (0.3 m), the metal culvert, which would be limited to a minimum depth of fill of 0.9 m (3 ft) under current practice, deflected vertically approximately 50 mm (2 in.), but no yielding was noted. Also, at the minimum depth of fill, the reinforced concrete arch culvert deflected about 1.5 mm (0.06 in.), and cracks on the underside of the crown opened to a width of about 0.01 in., the service stress limit. Those cracks closed when the live load was removed.

Computer models were calibrated against the field-test data. Two-dimensional analysis, with nonlinear elastic-plastic soil modeling, was used to analyze the effects of earth loads, and three-dimensional linear elastic analysis was used to analyze for live-load effects. The computer models were then extended to analyze five shapes and sizes of metal culvert and two shapes of concrete culvert to develop a body of data that could be used to generate simplified design equations. For metal culverts, the approach used was to develop equations for moments and thrusts due to earth and live loads; for concrete culverts, the approach was to develop simplified pressure distributions that could be used as input into computer-based frame analysis.

The development of simplified design procedures required a number of simplifying assumptions that make the procedures somewhat conservative. Thus, design by finite element analysis should remain as an alternative design tool; however, finite element analysis requires prior experience to select soil properties, design the mesh, and interpret results. Some additional guidance is provided on key issues of concern for the comprehensive design procedure.

Comparison with current practice was the primary means of assessing the proposed procedures, and the calibration work indicates that the proposed design procedures produce results consistent with current practice.

Modifications to current design practice for metal culverts that have been incorporated into the proposed design specifications include the following:

- Addition of a service limit state for deformation;
- Incorporation of flexibility factors for large-span culverts;
- Addition of strength limit states for flexure, combined thrust and flexure, and general buckling;
- Definition of the structural role of longitudinal and circumferential stiffeners;
- Development of more comprehensive procedures to evaluate earth load; and
- Development of procedures to compute moments due to construction, earth, and live loads.

Modifications to current design practice for large-span concrete culverts that have been incorporated into the proposed design specifications include the following:

- Addition of a limit state for radial tension,
- New procedures to determine earth load,
- New simplified pressure distributions for design by frame analysis, and
- A requirement that reinforcement for large-span culverts be designed according to reinforced concrete pipe procedures.

Detailed design examples are provided to demonstrate application of the procedures for both metal and concrete culverts.

The development of simplified procedures is not meant to prevent the use of more sophisticated methods of analysis, such as finite element analysis. The power of computer analysis by the finite element method is an important design tool; however, finite element analysis requires experience. Guidelines are provided for designers who wish to undertake culvert design by finite element analysis.

Construction specifications have also been developed. These specifications provide considerably more detail about the construction process than was previously available to field personnel. New aspects of the construction specifications include the following:

- Limiting the use of backfills that consist of uniform fine sands;
- Incorporating controlled, low-strength material as backfill;
- Having detailed procedures for important steps in excavating and backfilling large-span culverts;
- Improving consistency across different types of culverts;
- Improving terminology and definitions; and
- Requiring post-construction inspection.

Overall, completion of this project represents a significant step forward for the design of large-span culverts. Designers and constructors will have greatly improved tools available for designing and building these structures.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

Flexible and rigid large-span culverts, ranging in span from 3 m (10 ft) to occasionally more than 15 m (50 ft), are often a practical structure for short to intermediate span crossings, especially on local road systems. The use of these structures is growing; however, the available design and construction specifications have not been updated for many years, and modifications are needed to reflect current design theory and current construction practices as well as to take advantage of increased computational power for analysis.

Current design of metal culverts is largely experience based, and, with the exception of thrust, design forces are not computed. Also, stiffeners, called "special features," are required, but no structural role is assigned to them. Overall, current large-span metal culvert design lacks a suitable design model. Development of such a model is a particular need at this time, with AASHTO's desire to incorporate load and resistance factor design (LRFD) principles into the design of all bridge structures. LRFD requires a suitable design model to properly assess safety.

Current design of large-span concrete culverts is less empirical than that of metal culverts. However, several key parameters are still not defined, and the result is that designs may vary because of reasonable interpretations of the code. In particular, the total vertical earth load is not specified, even though concrete culverts are known to carry more soil load than just the weight of earth above them.

Current construction specifications for metal and concrete culverts also do not reflect current knowledge. Because large-span culverts depend on soil support for proper performance, it is imperative that the construction procedures be carefully specified and implemented.

This project addresses these issues through a review of current practice, full-scale field tests to address key issues, and computer modeling to extend the results of the field tests. Based on the results of these tasks, recommended specifications for design and construction of large-span metal and concrete culverts have been developed. The design methods in these specifications are simplified; they are suitable for incorporation into AASHTO specifications. A protocol for comprehensive analysis and design of large-span culverts by finite element analysis is also developed and presented.

CHAPTER 2

FINDINGS

ASSESSMENT OF CURRENT PRACTICE

Current practice for the design of large-span culverts is summarized in Appendix A of the research team's final report. Key findings related to current practice and potential improvements are summarized in this chapter. A key conclusion of the review and evaluation is that there are a number of deficiencies in current practice; however, that should not be construed to mean that current practice is producing unsafe designs. Instead, it means that current designs are based largely on experience, particularly in the case of large-span metal culverts. The empirical approach does not allow proper consideration of reliability, nor does it allow extension into larger culvert spans or new culvert shapes. Thus, there is a need to develop generalized design models.

Soil Properties and Soil Behavior

Large-span culverts are buried structures. Interactions of culverts with the soil in which they are embedded affect the loads, moments, thrusts, and shear forces that the culvert must carry to provide good service performance. Thus, proper consideration of the embedment is an important design consideration.

A significant general concern with current AASHTO specifications is that backfill is not considered part of the structural system. Lateral pressures on culverts are considered part of the load, but in fact these pressures form part of the resistance that helps culverts carry vertical earth loads. Also, it is difficult to determine whether the bedding reaction under a closed culvert (e.g., circle, ellipse, or pear shape) is a load or a resistance. Although the bedding reaction is a function of the applied vertical loads, its magnitude and distribution are determined by design decisions. See, for example, the standard installation, direct design (SIDD) design method used for concrete pipe (AASHTO 1998), in which the designer selects the pressure distribution, and this decision dictates both the loads and much of the structural response. For buried culverts, it is probably best to think of the soil-culvert combination as forming the structural system. Designers must make decisions about type and density of backfill as well as culvert parameters to complete designs. Thus, it is important to have soil and backfill information in the design specifications.

Once it is accepted that the soil embedment is a part of the structural system, the designer must be aware of other decisions that affect culvert performance. The width and stiffness of the structural embedment at the side of the culvert is a key parameter, yet current AASHTO specifications provide no guidance on the width of structural backfill. If the structural backfill is narrow, the stiffness of the soil beyond the structural embedment will also affect structural performance. American Water Works Association (AWWA) Manual M45 *Fiberglass Pipe Design* (AWWA 1995) provides a simple method for determining an effective composite soil modulus based on the stiffness of both the structural backfill and the surrounding embankment material as well as the width of the structural backfill. This project has also addressed the issue, as it affects vertical loads on culverts. See below and Appendix C for further evaluation.

Soil Properties

Since the start of this project, AASHTO has adopted provisions to improve design methods for thermoplastic culverts, including a new set of soil moduli to characterize soil stiffness for design. The values of the soil modulus were developed by McGrath et al. (1999; see also McGrath 1998) based on hyperbolic soil parameters developed by Selig (1988) during development of the AASHTO SIDD design method for concrete pipe. The design parameter proposed by McGrath is the constrained (one-dimensional) modulus, which McGrath suggests can be treated as equal to the traditional, but empirical, modulus of soil reaction E'. The constrained modulus values (Table 1) display an increase in soil stiffness with increasing depth of fill, a well-documented behavior of soil in confined conditions. The design values for Sn and Si soils in Table 1 are considered appropriate for the design of large-span culverts. Properties for Cl soils are included in the table for reference purposes only, as Cl soils are not considered acceptable backfill for large-span culverts. The table uses a two-letter, two-digit system to group soils. The letter designations are described and correlated with AASHTO and Unified Soil Classification System (USCS) soil classifications in Table 2. The two-number designation indicates the soil unit weight as a percent of maximum per the standard Proctor test (AASHTO T99).

Table 2 lists the SIDD soil group names as well as the suggested group names from Table 1. The SIDD groups are named for the USCS (ASTM D2487) classification of the

TABLE 1 Constrained modulus for backfill materials, M_{s-SB}, MPa

Stress Level (kPa)	Soil Type and Compaction Condition									
	Sn100	Sn95	Sn90	Sn85	Si95	Si90	Si85	Cl95	Cl90	Cl85
7	16.2	13.8	8.8	3.2	9.8	4.6	2.5	3.7	1.8	0.9
35	23.8	17.9	10.3	3.6	11.5	5.1	2.7	4.3	2.2	1.2
70	29.0	20.7	11.2	3.9	12.2	5.2	2.8	4.8	2.4	1.4
140	37.9	23.8	12.4	4.5	13.0	5.4	3.0	5.1	2.7	1.6
280	51.7	29.3	14.5	5.7	14.4	6.2	3.5	5.6	3.2	2.0
420	64.1	34.5	17.2	6.9	16.4	7.7	4.8	6.2	3.6	2.4

NOTES:

1. MPa = 145 psi
2. Compaction levels are % of maximum unit weight per AASHTO T99.
3. Values are secant moduli for the stress range from unstressed to the indicated stress level.

specific soils that were tested to develop the properties; however, these designations are often misconstrued to be limited to that specific member of the soil group—i.e., that soil group SW includes only SW soils and excludes SP, GW, and GP. Thus, to eliminate this confusion, the group designations are proposed as an alternative.

Also of interest in establishing soil properties is the need to evaluate a composite soil modulus if the culvert is set in a narrow trench and the native soil is soft. Leonhardt (1979) proposed a way to deal with this, which was modified by AWWA and published in *AWWA Manual M45 Fiberglass Pipe Design* (AWWA 1995). A portion of the AWWA table, suitable for use with large-span culverts, is reproduced in Table 3, with the terminology shown in Figure 1. With this approach, the value of the constrained modulus used in design is determined as follows:

$$M_s = S_c M_{s-SB} \tag{1}$$

where

M_s = constrained modulus for use in design, MPa (psi);
S_c = factor to account for native soil stiffness and trench width, from Table 3;
M_{s-SB} = constrained modulus of structural backfill, MPa (psi);
M_{s-N} = constrained modulus of native soil, MPa (psi);
W = width of structural backfill at widest part of culvert, m (ft); and
S = maximum culvert span, m (ft).

Soil Behavior and Metal Culverts

Current AASHTO practice for design of metal culverts does not consider soil properties as a variable. Specifications limit backfill materials to AASHTO A-1, A-2-4, A-2-5, or A-3 soils and assume that these materials provide equivalent service when compacted as per AASHTO construction specifications. A-1 and A-3 soils have fines limited to 25 percent with a maximum plasticity index of 6, whereas A-2 soils have up to 35-percent fines with a plasticity index up to 10. Consequently, the soils behave quite differently in both strength and stiffness. The SIDD design method, used by AASHTO for concrete pipe, classifies A-2-4 and A-2-5 in a group that has about 50 percent of the stiffness of A-1 and A-3 soils (McGrath et al. 1999). Comprehensive methods for predicting soil behavior (Duncan et al. 1980, Selig 1988) and simplified approaches (Howard 1977) also show this to be the case.

A-1 and A-3 soils are uniformly graded materials with limited fines but include uniform fine sands. McGrath et al. (1999) found uniform fine sands sensitive to moisture and difficult to work with as pipe embedment materials; they recommended additional limitations on the use of A-1 and A-3 soils:

- A maximum of 50 percent of the particle sizes may pass the 0.150-mm (No. 100) sieve, and
- A maximum of 20 percent may pass the 0.075-mm (No. 200) sieve.

If the engineer approves the use of A-1 or A-3 soils not meeting these criteria, design should be based on A-2 soils.

TABLE 2 Correlation of soil groups with standard classification groups

Soil Group	SIDD Soil	Representative Soil Types	
		USCS	AASHTO
Sn	Gravelly Sand (SW)	SW, SP, GW, GP	A1, A3
Si	Sandy Silt (ML)	GM, SM, ML Also GC, SC with less than 20% passing 75 µm	A2, A4
Cl	Silty Clay (CL)	CL, MH, GC, SC	A5, A6

TABLE 3 S_C values for modifying M_s to consider stiffness of native soil

		W/S			
		0.25	0.50	0.75	1.00
$\frac{M_{s-N}}{M_{s-SB}}$	0.1	0.15	0.30	0.60	1.00
	0.2	0.30	0.45	0.70	1.00
	0.4	0.50	0.60	0.80	1.00
	0.6	0.70	0.80	0.90	1.00
	0.8	0.85	0.90	0.95	1.00
	1.0	1.00	1.00	1.00	1.00

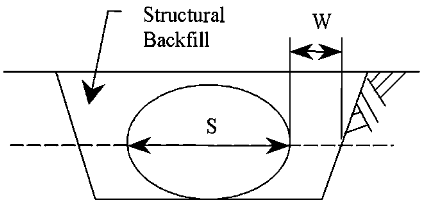


Figure 1. Terminology for trench width.

Soil Behavior and Concrete Culverts

Current AASHTO practice in the design of concrete large-span culverts is much less prescriptive than is the case for metal culverts. AASHTO soil classifications A-1 through A-6 soils are allowed for use as embedment for reinforced concrete pipe. For large-span culverts, current AASHTO specifications (AASHTO 1998) state simply that backfill shall be consistent with design assumptions. McGrath et al. (1999) recommend the same limitation on uniform fine sands for concrete culverts as for metal culverts.

Computer Modeling of Soil Behavior

Finite element analysis is now well developed for the design of buried culverts and consideration of the influence of the soil envelope. Katona and Smith (1976) developed the finite element computer program CANDE (computer analysis and design) under contract with FHWA solely for the purpose of culvert design. CANDE was later upgraded (Musser 1989) and is still widely used for culvert design, although a further upgrade is now desirable to take advantage of the Windows operating system and increased computing power. CANDE incorporates nonlinear, stress-dependent soil behavior, which is critical in modeling culvert behavior. Under current AASHTO practice, however, there is little opportunity to used CANDE for the design of metal culverts, because AASHTO restricts the soil properties, as discussed above. Other commercial finite element programs, such as ABAQUS and ANSYS, are incorporating soil models that make them suitable for analyzing buried culverts. These programs can also be used for full three-dimensional analysis, which is becoming more feasible as computer power continues to increase.

Analysis

Analysis for the design of large-span culverts in current practice varies widely. Under current AASHTO specifications, virtually no analysis is required, as design is largely based on a minimum gauge table and a simple calculation to evaluate hoop thrust. Finite element analysis is widely used for special installations and by researchers. The best known finite element program for design of culverts is CANDE, noted above.

CANDE analyzes culverts in two dimensions, and most culvert analysis is still carried out assuming two-dimensional response. This is acceptable for earth load, which is essentially a plane strain condition; however, live loads are inherently a three-dimensional problem, and there are significant shortcomings when two-dimensional analysis is applied to this type of loading. Moore and Brachman (1994) recently developed an approach to three-dimensional analysis with Fourier methods to determine the three-dimensional elastic response of culverts to surface live load. This approach has the advantage of using a two-dimensional finite element mesh and is considerably more efficient than conventional three-dimensional procedures; however, it is restricted to linear problems in which culvert or pipeline response is not affected by the ends of the structure. For this project, the Moore–Brachman procedure was selected as the best tool available for analysis of live-load effects on large-span culverts.

Design

There is a significant lack of consistency in culvert design practice. Design practices vary significantly from state to state; even within AASHTO standards, the procedures are allowed to vary dramatically, and not always logically, with culvert type. For example, Table 3.4.1.2 of the LRFD specifications provides four separate load factors ranging from 1.3 to 1.95, for vertical earth load on different types of buried culverts. This table is indicative of the variety of approaches that have been taken in culvert design based on differences in traditional design methods, materials, and geometry. Inconsistency also results from attempts to make culvert design practice fit the design models used for other types of structures. For example, the LRFD specifications consider active and at-rest earth pressure as loads and consider passive pressure as a resistance; yet, in culvert design it is very difficult to define the effects of lateral pressure as active or passive. A single treatment should be developed.

The state-of-the-art review presented in Appendix A of the research team's final report identified several areas of inconsistency in AASHTO practice as they relate to long-span culverts and, in many cases, all culverts.

Live-Load Distribution Through Fills

The AASHTO LRFD specifications (AASHTO 1994, 1998) made significant changes to the procedures for distributing live loads through fills. The LRFD specifications incorporated consideration of the tire footprint at the ground surface, relative to the standard specifications (AASHTO 1996), which applied wheel loads as a point load. However, the LRFD specifications restricted the rate of spread with increasing depth of fill, from 1.75 to 1.15 or 1.0, depending on the type of backfill. The LRFD specifications considered the distribution of loads through fills without considering the effect of the structure. Test results produced as part of this project as well as prior research indicate that live loads spread over a much greater area of structure than allowed by the LRFD specification.

The reason for this difference varies with metal and concrete culverts. Metal culverts deform under live load. This deformation causes the development of shear stresses in the soil that cause the live-load effect to spread out through the soil and over a larger area and mobilize a greater length of culvert to resist the loads. In concrete culverts, which are rigid, the reaction is somewhat different. The concrete culvert does not deform significantly under load; however, concrete culverts are so stiff that they internally spread the load over a greater length of structure than indicated by the LRFD specifications.

Earth Loads in General

Treatment of earth loads on large-span culverts is also variable in current AASHTO specifications. A trend in recent AASHTO specifications has been to specify loads in terms of the vertical arching factor, which relates the load on the pipe in terms of the soil prism load. The soil prism load is the weight of soil directly over the culvert:

$$W_{sp} = \gamma_s (H + K_{VAF} R_u) S \tag{2}$$

where

W_{sp} = soil prism load, kN/m [kips/in. (k/in.)];
H = depth of fill over top of culvert, m (in.);
γ_s = unit weight of soil, kN/m^3 (k/in.^{3});
K_{VAF} = factor to account for span/rise ratio;
= 0.21 for circular culverts;
= 0.172 + 0.019 (S/R_u) for other shapes;
S = culvert span, m (in.); and
R_u = upper rise, distance from widest point of culvert to top of culvert, m (in.).

The load on the culvert is then determined as

$$W_E = \mathrm{VAF} W_{sp} \tag{3}$$

where

W_E = earth load on culvert, which is defined as total springline thrust (sum of thrust at both springlines), kN/m (k/in.); and
VAF = vertical arching factor to account for soil–culvert interaction effects.

AASHTO has already adopted Equation 3 for concrete (VAF ~ 1.4) and thermoplastic pipe (VAF varies from about 0.25 to 1.0). The same approach is recommended for large-span culverts.

Earth Load for Metal Culverts

For large-span metal culverts, the current AASHTO specifications provide the following equation to compute the earth-load thrust:

$$T = PR_t \tag{4}$$

where

T = earth-load thrust, kN/m (k/in.);
P = crown pressure, kPa [kips/in.^{2} (ksi)]; and
R_t = radius of top plates, m (in.).

However, no guidance is provided for computing crown pressure. Experienced designers would likely assume that the crown pressure is the free field soil stress (unit weight of soil times depth of fill), but a novice designer would have no basis for making that decision. Equation 4 also ignores the weight of soil on the shoulders (the area over the culvert that is below the crown), which can be significant for large-span culverts at shallow depths. The VAF for Equation 4 varies from 0 for $H = 0$ to 1.3 for a culvert with deep fill and a span/upper rise ratio, S/R_u, of 3. This is contrary to the parametric study of large-span metal culverts undertaken as a part of this project and reported in Appendix D. This study (and prior work by Duncan 1978, Haggag 1989) proposes that the VAF should be high for shallow-buried culverts and that it decreases with increasing depth of fill. The proposed equation is presented and discussed in Chapter 3. For typical large-span culverts with S/R_u ratios of about 3, the arching factor varies from about 2.5 for shallow cover to about 1.2 for deep cover.

Earth Load for Concrete Culverts

AASHTO does not currently specify a VAF for large-span concrete culverts, nor does it specify vertical design load in any other fashion. Because most long-span concrete culverts are designed based on pressure distributions instead of using VAF to determine thrust, a slightly different approach is used for concrete culverts. The parametric study of concrete culverts conducted as part of this project and presented in Appendix D suggests that the vertical pressure at midspan should be the same as the free field soil pressure (essentially, VAF = 1 locally), and the vertical pressure at the edge of the culvert should be 1.2 times the free field soil pressure (essentially, VAF = 1.2 locally). The net effect of this soil pressure distribution is a VAF that varies from about 1.2 for shallow culverts to 1.1 for deep culverts. This is discussed further in Chapter 3.

Design Model for Metal Culverts

Flexural Capacity

Current practice has no limit state that addresses the structural capacity of large-span metal culverts except for thrust

(AASHTO 1994, 1996). Thus, the current design model has no means for incorporating several significant aspects of culvert behavior. It has long been proposed and accepted that deeply buried metal culverts can be designed solely on the basis of hoop compression capacity (White and Layer 1960). However, it is clear that large-span metal culverts need flexural stiffness to resist construction loads, and they need flexural strength to resist live-load moments. It is important to remember that large-span metal culverts are generally installed under relatively shallow depths, with depth-of-fill/span ratios typically less than 1.0 and often less than 0.1; thus, they are subject to nonuniform soil pressures. The following two aspects of the proposed design method address this:

- Use of the flexibility factor to control minimum stiffness is extended to large-span culverts; however, the stiffness used to meet the requirement incorporates the benefit of circumferential and/or longitudinal stiffeners (see below for more discussion of the role of stiffeners, referred to as special features); and
- Moments due to construction and live loads are considered in design.

Special Features

Special features are used on large-span metal culverts to increase the culvert strength and stiffness and to improve the response to installation forces. The following two types of special features are allowed:

- Circumferential stiffeners: typically steel angles or corrugated plate that are bolted to the top arc, parallel to the span of the culvert; and
- Longitudinal stiffeners: reinforced concrete beams attached to the culvert where the top and side plates meet (also called thrust beams).

Current AASHTO specifications require that large-span metal culverts incorporate a special feature; however, the specifications make no provisions for the strength or stiffness of a special feature or for how such features should be attached to the structure. Thus, there is no method for incorporating a special feature into a design model.

The role of circumferential stiffeners in culvert design has always been clear—the flexural capacity of the section is increased; however, as noted above, because current design procedures include no limit state to address flexural capacity, this increased capacity cannot be specifically incorporated into a design model. In the proposed design model, circumferential stiffeners are used for two purposes: (1) to meet the minimum stiffness requirements and (2) to meet the flexural capacity requirements in service.

The role of longitudinal stiffeners is less clear and has been more controversial than that of circumferential stiffeners. In two-dimensional analysis, which has been the basis for most large-span culvert design, there is no apparent benefit to using longitudinal stiffeners. In three-dimensional analysis, however, longitudinal stiffeners help to distribute construction loads along the length of a culvert, thus reducing the peaking and distortion that occur while placing and compacting backfill. In the proposed design model, the longitudinal stiffener increases the stiffness of the culvert to resist construction loads (minimum stiffness requirement), but it is not considered to increase the overall flexural capacity.

General Buckling Capacity of Large-Span Metal Culverts

All structures subjected to compression forces may be destabilized by buckling. Buckling has long been considered a limit state for flexible pipe; however, theories for buckling of buried pipe (AASHTO 1994) were known to be excessively conservative for large-span culverts, and buckling was dropped altogether as a limit state. Moore (1994) has now shown that the older buckling theories, based on the Winkler model, were conservative because of simplifications associated with the model. The Winkler model assumes a buried pipe is supported by discreet springs around the circumference. However, when the soil support is modeled as continuous, there is a change in the relative contribution of soil and culvert to total buckling capacity, so that the capacity predicted for large-span culverts increases to realistic levels (Appendix D).

Compaction Effects

A significant shortcoming of current practice is the control of deflections and stresses induced by compaction in metal culverts. This is both a design problem and a construction problem. From a design point of view, it is almost impossible to predict construction deformation, which varies with small changes in backfill type and/or moisture content, size, number of passes of compaction equipment, lift thickness, and many other variables. McGrath et al. (1999) offered a simple approach for predicting construction pressures that considers magnitude of construction equipment and friction angle of the backfill. This method is not sufficiently developed for incorporation into design specifications, but it likely captures the key parameters. It suggests that compacting backfills with lower friction angles (silts relative to sands and gravels) will increase deformation, even if the same compaction force is applied to the materials. This, in turn, suggests that long-span metal culverts to be embedded in silt backfill should have a higher stiffness than those to be embedded in sand or gravel.

During construction, AASHTO specifications rely on the presence of a shape control inspector, provided by the manufacturer, to control deformation during backfilling. The review of available knowledge about appropriate procedures, detailed in Appendix A of the research team's final report, shows that

AASHTO construction specifications could be more detailed, thereby providing a better opportunity for Department of Transportation employees to understand the key issues in the process.

Incorporation of flexural limit states requires that the moments due to construction effects be considered; however, as just noted, these effects are virtually impossible to predict. The proposed method for controlling these forces is a form of reverse engineering. Changes in culvert shape are the result of flexural deformations, and it is clear from current construction practice that deformations during backfilling can be controlled. Thus, by assuming a limiting deformation in the field, an associated moment can be back-calculated by using the fundamental relationship between moment and curvature:

$$M = \Delta\rho(EI) \tag{5}$$

where

M = moment, kN-m/m [kip-in./ft (k-in./ft)];
$\Delta\rho$ = change in curvature, 1/m (1/in.);
E = modulus of elasticity of culvert, kPa (ksi); and
I = moment of inertia of culvert, m^4/m ($in.^4$/ft).

Design Model for Concrete Culverts

For reinforcement design of large-span concrete culverts, designers are currently referred to AASHTO procedures for general concrete structures. An alternative is to design in accordance with the AASHTO procedures for reinforced concrete pipe, which have been in use for over 15 years (Heger and McGrath 1982). The benefits to using the pipe equations include the following:

- The design method is complete and is easily used in practice.
- The design method includes a provision for the radial tension limit state that applies to curved concrete sections.
- The pipe procedure for shear strength is readily applied to uniformly loaded, curved members where strength must be evaluated at any location instead of at a rigid support point as in most concrete beams.
- The procedure for crack control is well founded and considers important variables that are not considered in other AASHTO procedures for evaluating crack control.
- The procedures are based on substantial test data, although none are specifically for arch culverts.

Construction of Large-Span Culverts

Large-span culverts all depend to some extent on soil support. They must be installed on stable foundations and require lateral soil support to control deformations, moments, thrusts, and shears. This dependence on soil support suggests that construction specifications should be detailed and provide extensive guidance to contractors erecting and backfilling them. Abdel-Sayed et al. (1993) and Selig et al. (1977) have written extensively on the subject, and manufacturers have also developed guidelines; however, in general, a great deal of responsibility lies on the shape control inspector, who is required to be present during backfilling. Key general issues that should be addressed in the specifications include the following:

- Backfill materials must be controlled; McGrath et al. (1999) suggested that uniform fine sands be eliminated from acceptable backfill materials or, if they are included, that they be treated as silts.
- Criteria for evaluating the risk of migration of fine soils into open-graded backfill materials should be evaluated.
- Shape control limits need to be set as a part of the design process; as noted above, development of a design model based on flexural capacity must consider the moments due to construction practices; thus, limits on shape must be set in the contract documents.
- Backfill placement and compaction effort must be controlled properly.

FIELD TESTS

Review of current practice in design and construction of large-span culverts showed some areas where more information was required to develop new design models. To address this need, two full-scale field tests were conducted at the University of Massachusetts at Amherst. The findings of the tests are presented here. Complete details are presented in Appendix B and by Webb (1998) and Webb et al. (1998).

Objectives

The tests were designed to meet the following primary objectives:

- Investigate structural response of culverts during backfilling,
- Investigate structural response of large-span culverts under conditions of shallow fill and live loads,
- Investigate response of a large-span metal culvert without special features,
- Investigate pressure distribution on a large-span reinforced concrete culvert, and
- Develop data for use in calibrating computer programs used to model behavior of large-span culverts.

Test Plan

The tests were conducted on a large-span reinforced concrete arch culvert and a large-span structural-steel-plate arch culvert. The span and rise of both test culverts were approxi-

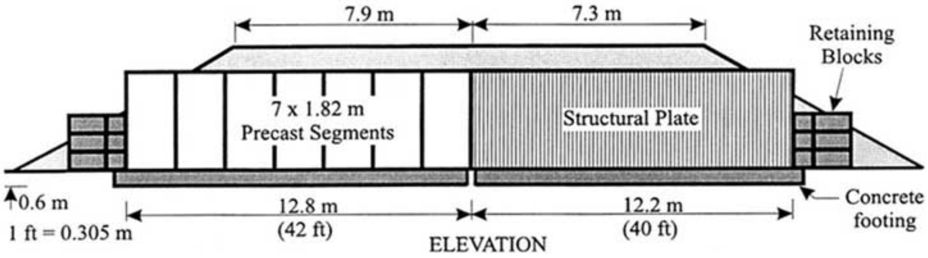


Figure 2. End-to-end arrangement of test culverts.

mately 9.3 and 3.6 m (30.5 and 11.8 ft), respectively. The concrete culvert was precast and delivered to the site in 1.8-m (6-ft) segments. The metal culvert was assembled on site from corrugated structural plate. Both the metal and concrete culvert were sized for installation at the minimum cover depths recommended by AASHTO.

The culverts were installed end to end in a single trench (Figure 2). Because the test program was developed to evaluate response to live loads, this arrangement was acceptable as the live-load response would be local to the loaded area, and interaction of the two dissimilar culverts would be minimal. The typical installation cross section is shown in Figure 3. The metal culvert was installed without any special features.

The culverts were instrumented to monitor deflections, interface pressures, culvert strains, soil strains, and relative movement of precast concrete elements.

The culverts were to be backfilled to a depth of 0.9 m (3 ft) and subjected to live load. The fill was then reduced in steps to depths of 0.6 and 0.3 m (2 and 1 ft), and the live-load tests were repeated at each depth. The live-load tests were conducted with a vehicle loaded to represent an AASHTO design tandem truck increased by 40 percent to represent impact loading. Total load on the tandem axles was 310 kN (70,000 lb). Data were collected while the live-load vehicle was positioned at several locations across the culvert.

Two sets of tests were conducted. The first installation used a well-graded, clean sand backfill compacted to 92 percent of maximum standard Proctor density. The second test used the same backfill but without compaction. In this second test, the material achieved about 85 percent of maximum standard Proctor density. After the second set of live-load tests was completed, the depth of fill over the culverts was raised to 1.5 m (5 ft), and the behavior was monitored for 9 months.

Results

During backfilling, the top of the metal culvert moved upward about 72 mm (2.8 in.) in Test 1 with compaction and 53 mm (2.1 in.) in Test 2 without compaction. During Test 2, the metal culvert also moved to one side, and the plates flattened out slightly. In both tests, the upward movement (peaking) of the metal culvert developed at a faster rate than recommended by the manufacturer. Therefore, during backfilling, the top of the culvert was loaded with concrete blocks to control the peaking. During normal construction, the manufacturer recommends using backfill on top of the culvert for the same purpose, but this is not often required. The test structure may have peaked this much because the ends were free, whereas the ends of a typical culvert would be cast into a headwall, thus providing considerably more restraint.

During backfilling, the crown of the concrete culvert moved upward about 1.5 mm (0.06 in.) in both tests as the backfill was raised to the top of the structure and then returned close to the original position after backfill was placed over the top of the culvert.

The live-load vehicle created a wave type motion in the metal culvert as it moved across the surface above the culvert. As the vehicle approached the shoulder, the crown moved up and away from the vehicle; then, as the vehicle reached the

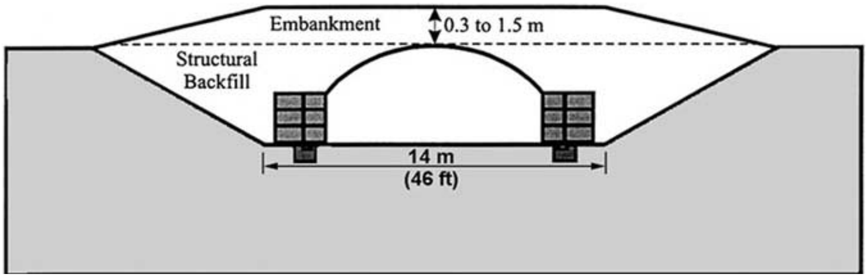


Figure 3. Cross section of culvert test arrangement.

culvert centerline, the crown moved back to center and downward under the load. Finally, as the vehicle moved off the culvert, the crown again moved up and away from the load. This behavior was most evident in the tests at 0.3 m (1 ft) of cover (Figure 4).

Longitudinal distribution of live-load effects on the metal culvert is demonstrated in Figure 5 for the three depths of fill in Test 1. In this figure, the arrows represent the locations of the vehicle wheels during two passes. At all depths, the culvert develops a single deflection wave, which suggests that the two sets of dual wheels interact. Current practice for loading culverts suggests that the wheels act separately at a depth of 0.3 m.

The concrete culvert displacements under live-load testing were minimal, never exceeding 1.5 mm (0.06 in.). During the live-load testing at 0.3 m of fill, flexural cracks on the inside of the crown opened up to a maximum width of about 0.28 mm (0.011 in.). The typical service load limit for crack widths in concrete culverts is 0.25 mm (0.01 in.). All cracks closed up to a hairline width after the live load was removed. Virtually all the cracking in the concrete culvert developed during shipping and installation of the segments.

Neither the metal culvert nor the concrete culvert showed any signs of yielding during backfilling or during the live-load tests. In the metal culvert, this observation was confirmed with strain gauge measurements.

Moments in the metal culvert due to 0.9 m (3 ft) of earth cover are presented in Figure 6, which shows negative moment at the crown due to the peaking and positive moment where the radius of curvature changes from the top radius to the side radius (SC, NC, called the curvature points). Figures 7 and 8 show the moments in the metal culvert due to the live-load vehicle when positioned at the shoulder (SH) and crown (CR), respectively, at depths of 0.9, 0.6, and 0.3 m (3, 2, and 1 ft) of cover. The figures show a significant increase in moment with reducing depth of cover. The crown moments from Test 1 were about two-thirds of the crown moments in Test 2, whereas the shoulder moments were similar for both tests.

For the concrete culvert, much of the information derived from the tests was taken from measurements with earth pressure cells located around the perimeter of the test culvert (Figure 9). The wheel positions for the various live-load positions are shown in Figure 10. The tire inflation pressure, and thus the contact pressure, at the surface was about 550 kPa (80 psi). The measured contact pressures on the culvert were much lower, even at a depth of 0.3 m: the maximum pressure was 100 kPa (14.5 psi) at a depth of 0.3 m and 50 kPa (7.6 psi) at a depth of 0.9 m (3 ft). Longitudinal distributions of live-load pressures on the concrete culvert for the tests at 0.9 and 0.3 m are presented in Figures 11 and 12, respectively.

Figure 11, for the live-load tests on the concrete culvert at 0.9 m of cover, shows the highest pressures at the S-T gauges, located just off the crown, when the live-load vehicle is located at the shoulder (SH) and the crown (CR). As indicated in Figure 10, these truck positions put an axle almost directly over the S-T gauges. Figure 11b shows much lower pressures at the crown gauges because the axles are straddling the gauges when tandem axles are centered over the crown. Figure 12 shows much higher pressures in the S-T gauges when the cover depth is reduced to 0.3 m. This is expected. The crown gauges show lower pressures when the depth is 0.3 m, which again is expected, because the wheel loads straddle the gauges and, with shallower cover, there is less depth of fill for the load to spread through the soil and load the gauges. If the crown gauges were located directly under the wheels, we would expect a higher pressure than shown by the S-T gauges, which are at a slightly greater depth.

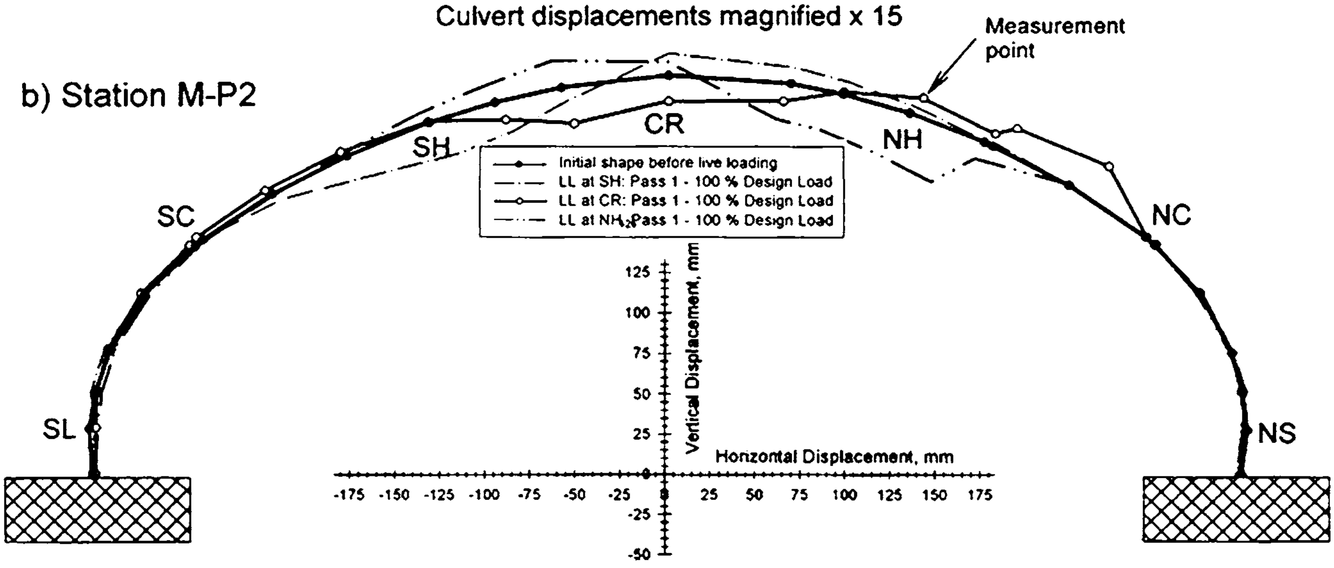
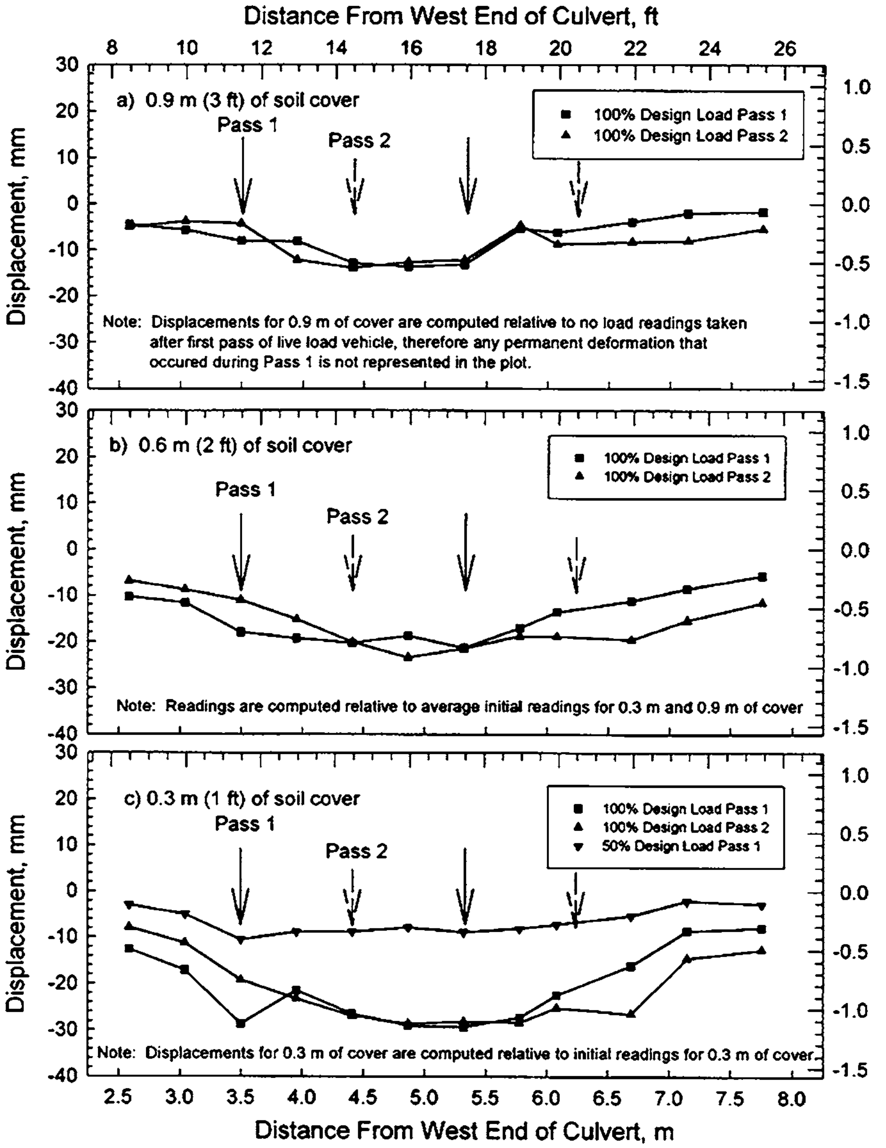
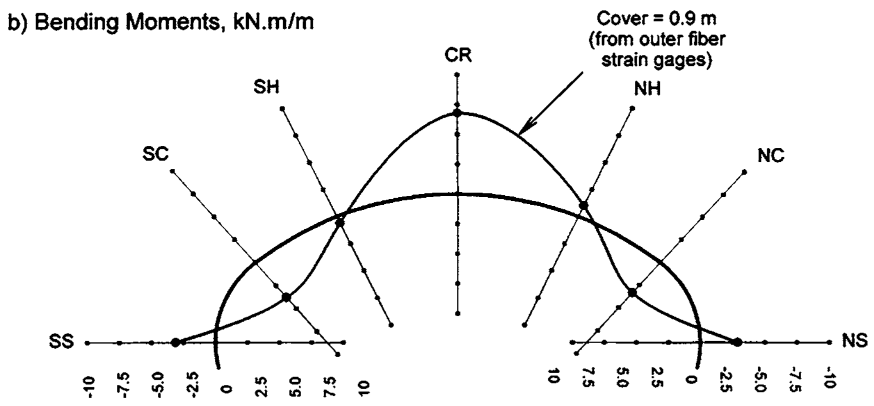


Figure 4. Metal culvert live-load displacements: Test 2, 0.3-m cover.



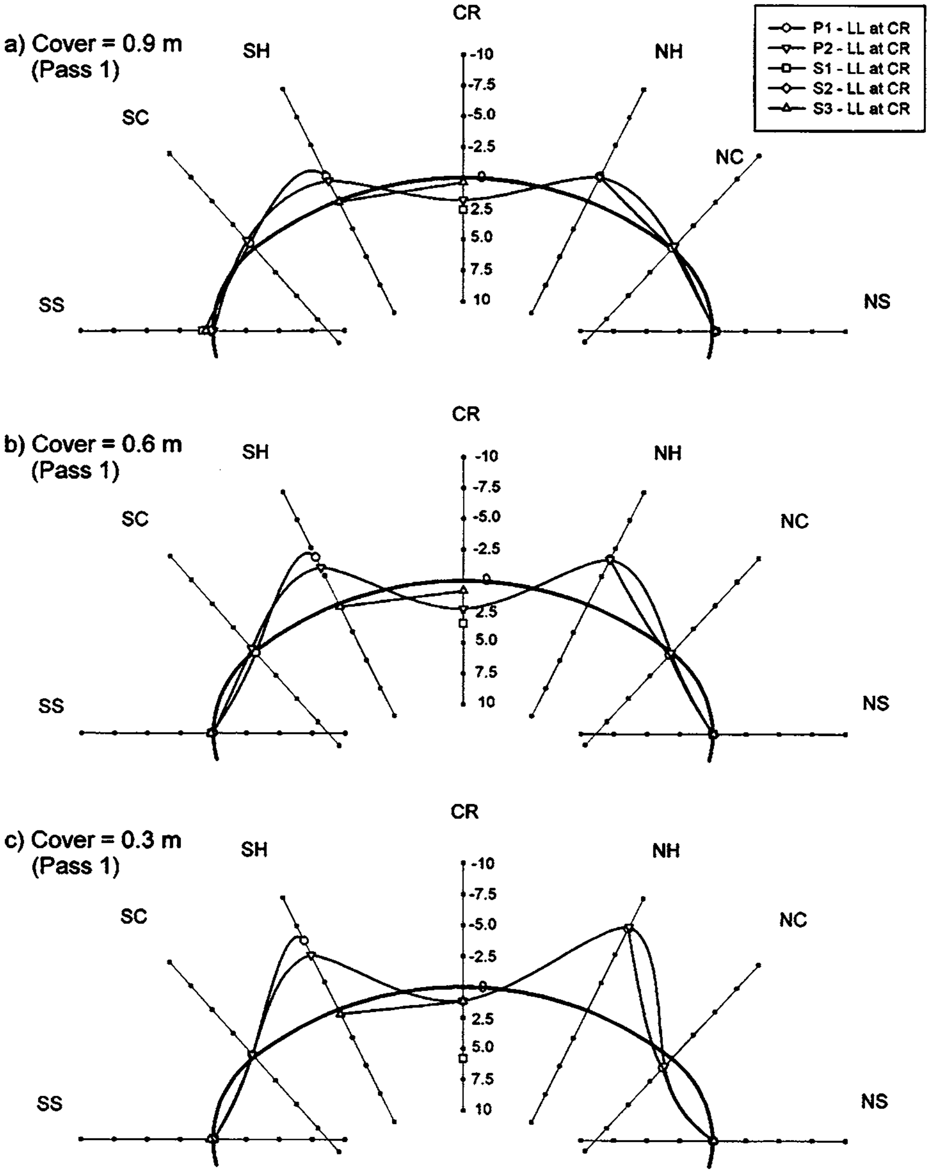
Notes: 1. Positive displacement is upward movement
2. See notes on plots for zero references

Figure 5. Longitudinal deflection profile of metal culvert crown under live load: Test 1.



Note: Positive bending moment is tension on inside fiber

Figure 6. Moments due to earth load: Test 1, 0.9-m cover.



Note: Positive bending moment is tension on inside fiber (Units of kN.m/m)

1 in.-k/ft = 0.37 kN-m/m

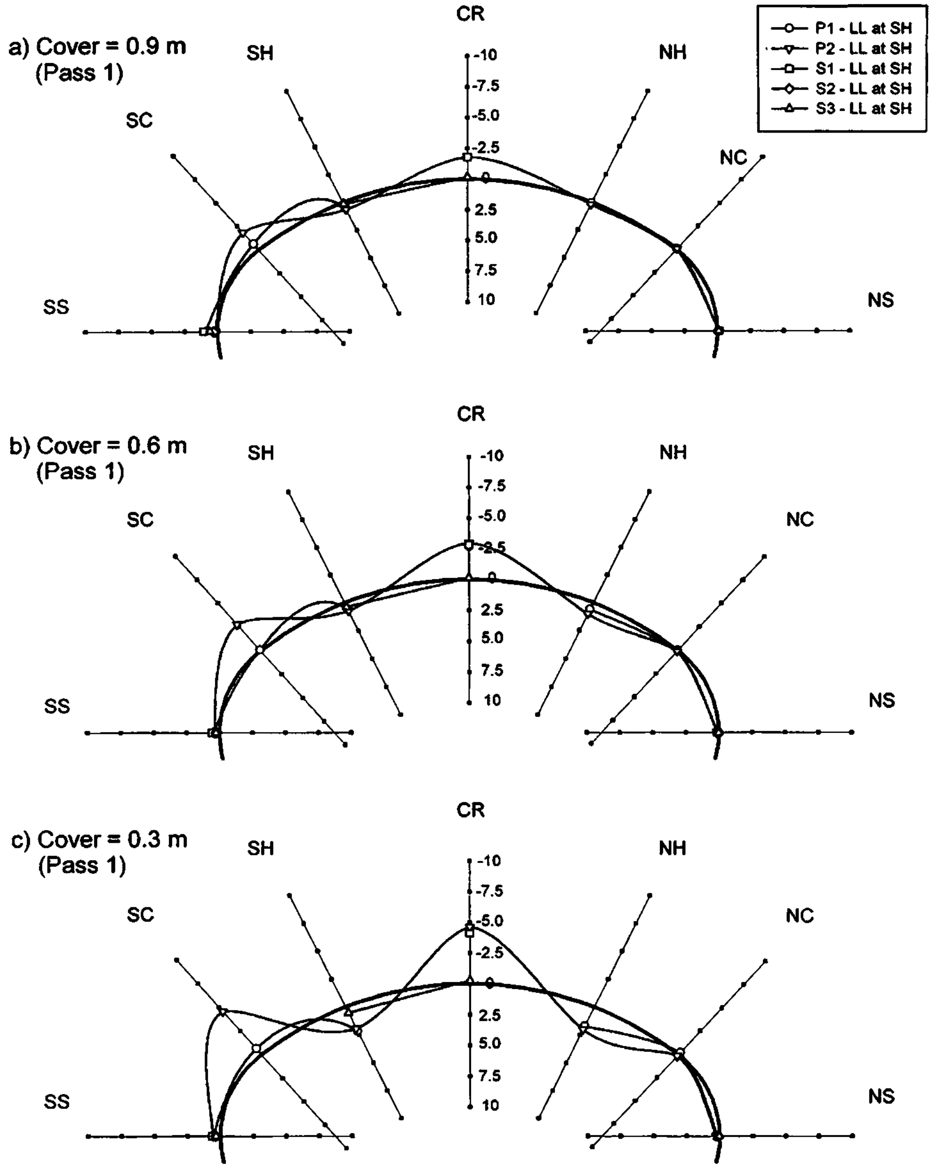
Figure 7. Moments due to live-load vehicle located over crown: Test 1.

Live-load pressures on the metal culvert were more distributed than on the concrete culvert, resulting in lower contact pressures (Figure 13). This suggests that the metal culvert deforms under the live-load pressure, allowing the load to distribute over a broader area as a result of shear stresses in the soil. In contrast, the concrete culvert develops much higher pressure but distributes load internally due to the high stiffness of the culvert. Both the metal and the concrete culvert mobilize a significant length of culvert to resist live loads.

Foundations under the metal and concrete culverts showed minimal movement during the tests. Foundations settled about 4.5 mm (0.18 in.) because of backfilling. No detectable footing settlement was measured during live-load testing. No rotation or lateral movement of the footings was detected for any of the tests.

ANALYTICAL MODELING

Finite element computer models of large-span culvert performance were an important part of the design method development. Existing models were used to predict performance in the field tests and were then calibrated against the results of the field tests. After the field tests were used to gain confidence in the predictive ability of the finite element analysis, the models were used in a parametric study to analyze the



Note: Positive bending moment is tension on inside fiber (Units of kN.m/m)

1 in.-k/ft = 0.37 kN-m/m

Figure 8. Moments due to live-load vehicle located over shoulder: Test 1.

performance of large-span sizes, shapes, and depths that were not considered in the field tests. The results of these extended analyses were used to develop simplified predictive equations for use in proposed AASHTO specifications.

Details and findings of the computer modeling are presented in Appendix C (field test models) and Appendix D (parametric study) and are summarized here.

Field Tests

Computer models of the field tests were first used to predict the magnitude of response of various parameters that might be measured in the field tests. This assisted in designing the tests and in instrumentation. After the field tests were conducted, the results were analyzed further to evaluate the performance of the programs and to calibrate them for further use in the parametric studies. Two-dimensional, nonlinear analysis was used to model the response to earth load; three-dimensional, linear analysis was used to model the response to live loads (Taleb and Moore, 1999, Moore and Taleb, 1999).

Both two- and three-dimensional analyses used linear soil models with a variable modulus dependent on the initial depth from the surface. In the two-dimensional analysis, the model was further extended to consider plastic soil deformation if the Mohr-Coulomb strength criterion was exceeded.

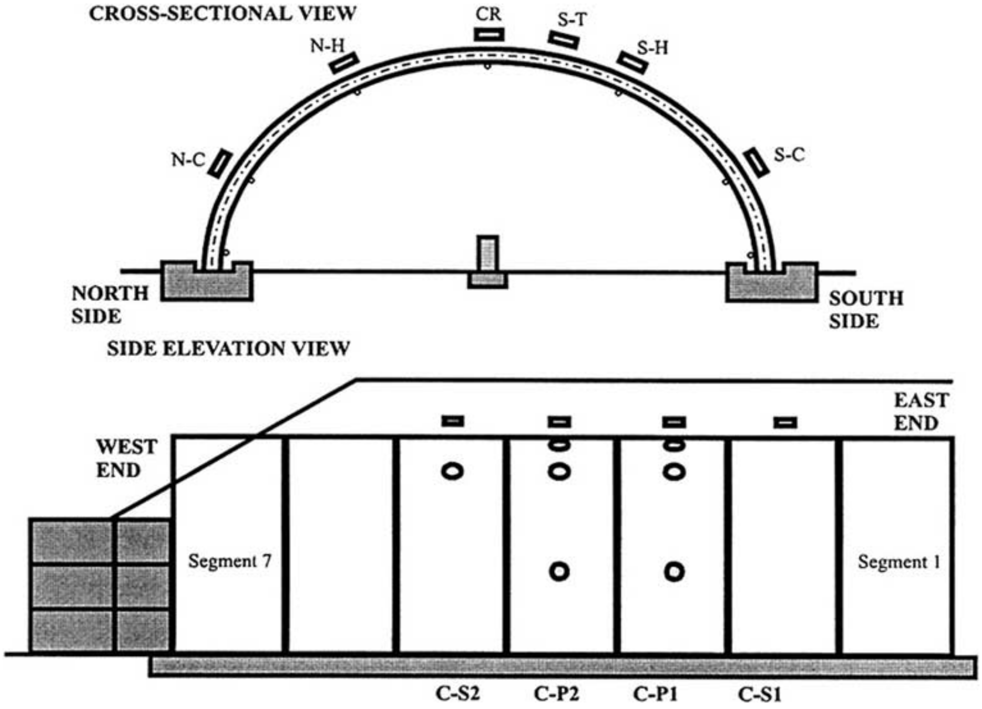


Figure 9. Locations of earth pressure cells around concrete culvert.

Modeling Compaction Effects

Part of the modeling effort investigated the ability of the programs to predict deformations due to compaction effects. Prior efforts have been made in this area (Katona 1978, Seed and Duncan 1983, McGrath et al. 1999); however, no satisfactory and generally applicable model has yet been developed. Part of the difficulty in predicting compaction effects is the inherent variability of soil materials, the wide variety of equipment available, and the almost infinite ways construction equipment may be used. This study investigated the possibility of calculating upper-bound construction deformations by imposing passive earth pressures in the soil mass at the side of the culvert and then enforcing equilibrium on the soil culvert system, allowing the culvert to deform to adapt to the lateral pressures. Results of the investigation are included in the following sections.

Metal Culvert Tests

Figure 14 presents the measured and calculated vertical displacement of the crown of the metal culvert due to earth load. The figure shows the computer predictions that were made before the tests (Class A) and the post-test predictions that include the effect of top loading with and without compaction forces. The behavior of the test culvert is best captured by the computer model that includes compaction; interestingly, this is the case for the compacted backfill (Test 1) as well as the uncompacted backfill (Test 2), which suggests that the process of placing the backfill imposes much of the uplift force on the culverts.

Figure 14 indicates that the proposed compaction model is effective when construction is carefully controlled, as it was for this test. There are insufficient data, however, to conclude that the proposed compaction model is generally applicable for all construction conditions.

Figure 15 compares the computer calculations of shoulder thrusts for the pretest analysis and for the post-test analysis with and without compaction. The strain gauge data for thrust were not considered reliable and are not reported. The figure indicates that thrust calculations are consistent and are not affected by the use of the finite element compaction model.

Figure 16 makes the same comparison for the crown moments. It shows that the finite element model of compaction has a significant effect on bending moments. The data indicate that, during backfilling, up to a depth of about 3 m (10 ft) above the footings, which is approximately the top of the culvert, the field moments fall between the calculated moments with and without the compaction model. At the final depth of fill, in Tests 1 and 2, the computer model without the compaction effect best represents the moments.

Culvert response to live loads is evaluated in Table 4 at a depth of 0.3 m (1 ft) for deflection and moment and at 0.6 m (2 ft) for thrust. The table compares the results of the two- and three-dimensional analyses with the field tests and indicates that deflections are computed reasonably accurately by two- and three-dimensional analysis, but the moments and thrusts are more accurately calculated by the three-dimensional

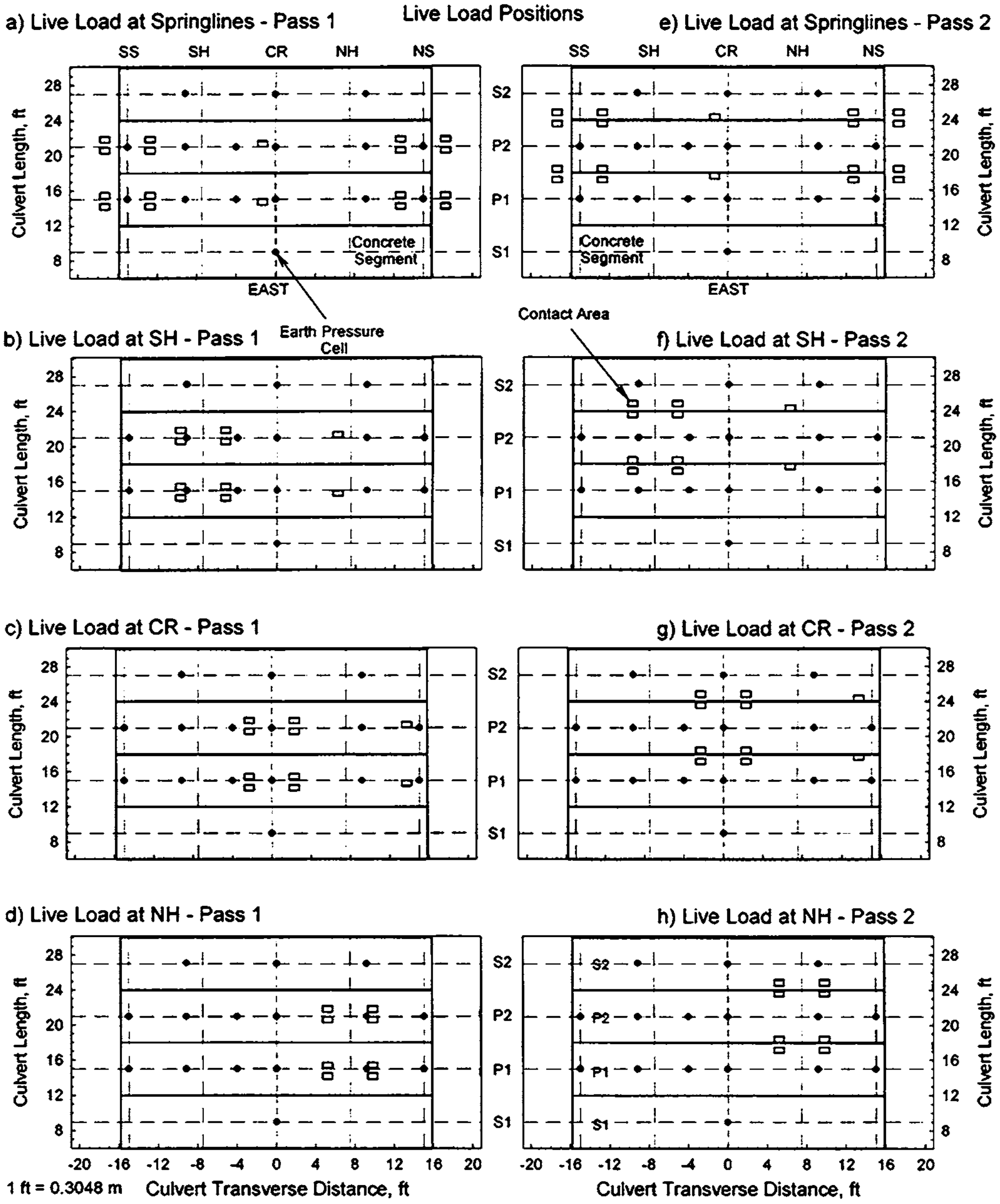


Figure 10. Truck positions for live-load vehicle over concrete culvert.

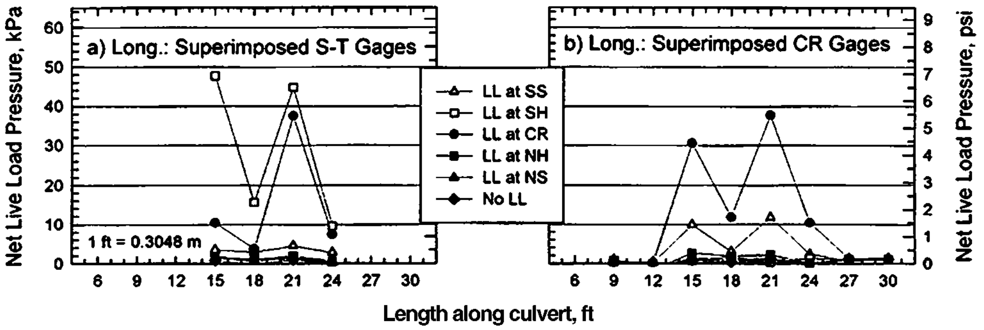


Figure 11. Longitudinal distribution of live-load pressures on concrete culvert: Test 1, 0.9-m (3-ft) cover.

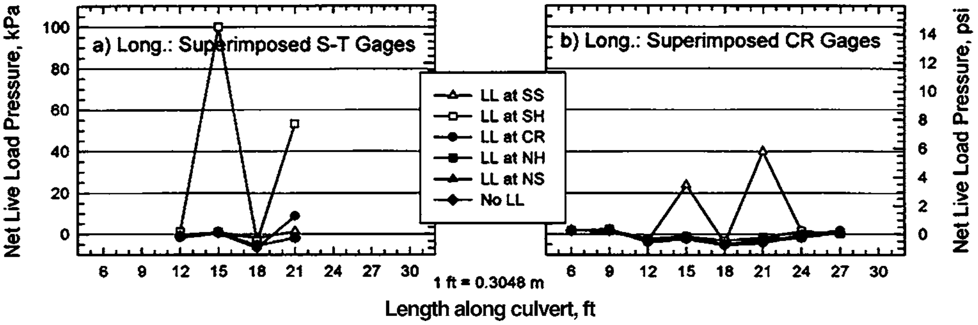


Figure 12. Longitudinal distribution of live-load pressures on concrete culvert: Test 1, 0.3-m (1-ft) cover.

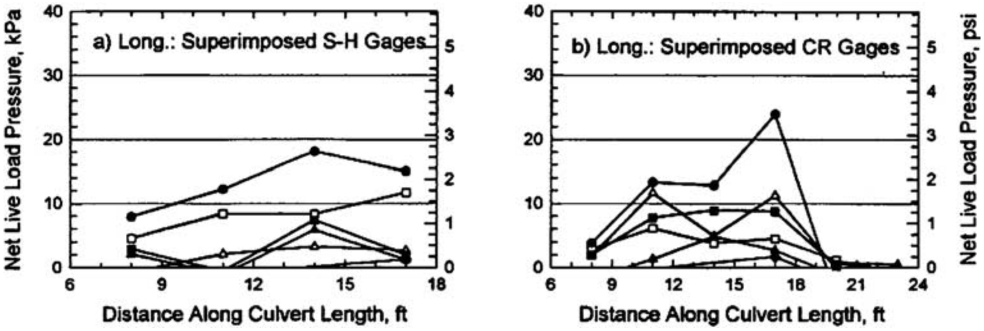


Figure 13. Longitudinal distribution of live-load pressures on metal culvert: Test 1, 0.9-m (3-ft) cover.

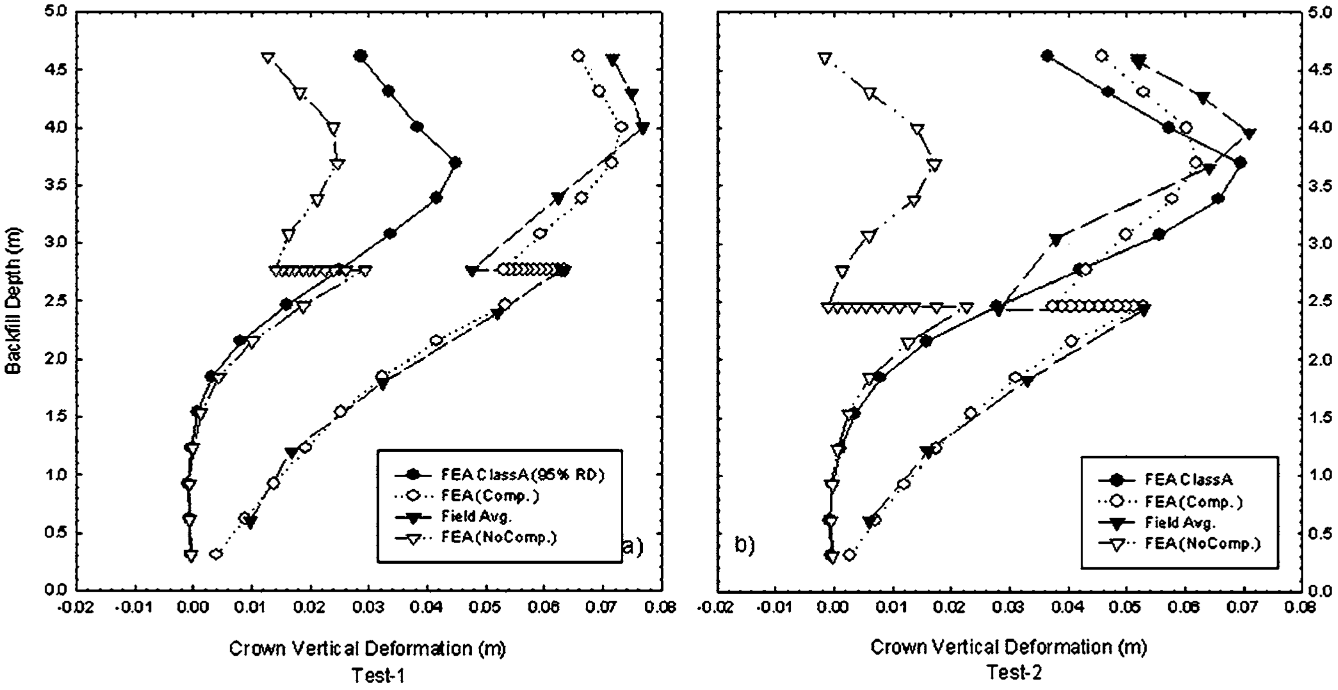


Figure 14. Comparison of field data and computer model predictions for metal culvert crown deflections during backfilling: (a) Test 1, compacted; (b) Test 2, loosely placed backfill.

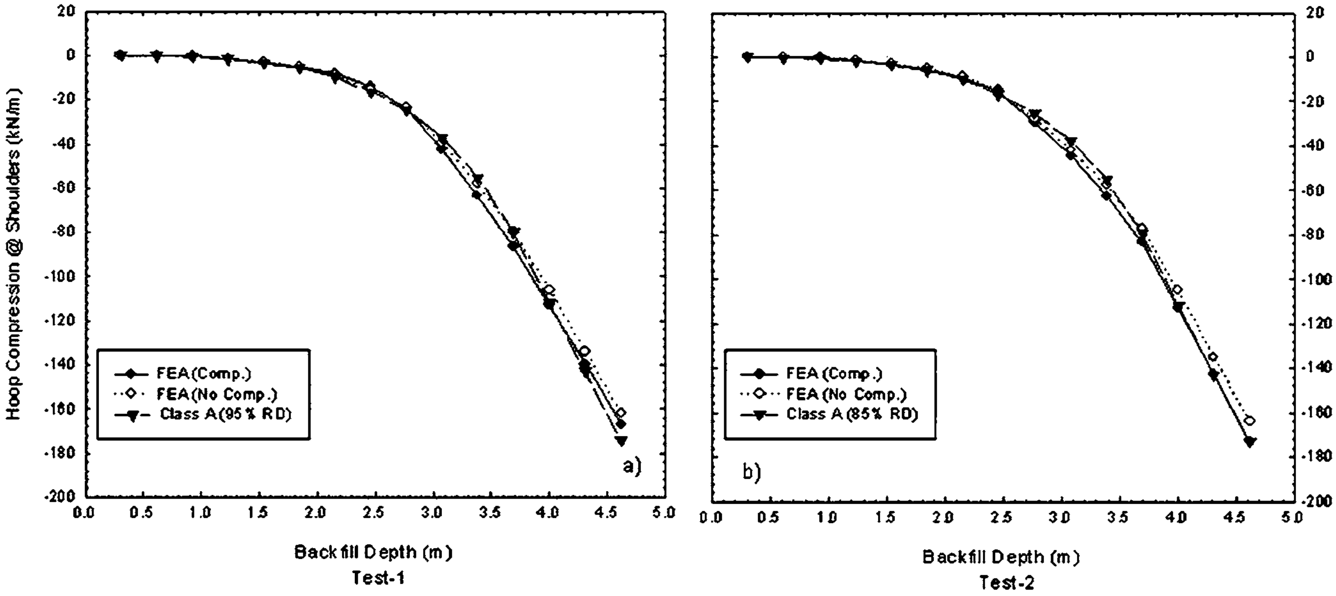


Figure 15. Shoulder thrusts: (a) Test 1, compacted; (b) Test 2, uncompacted.

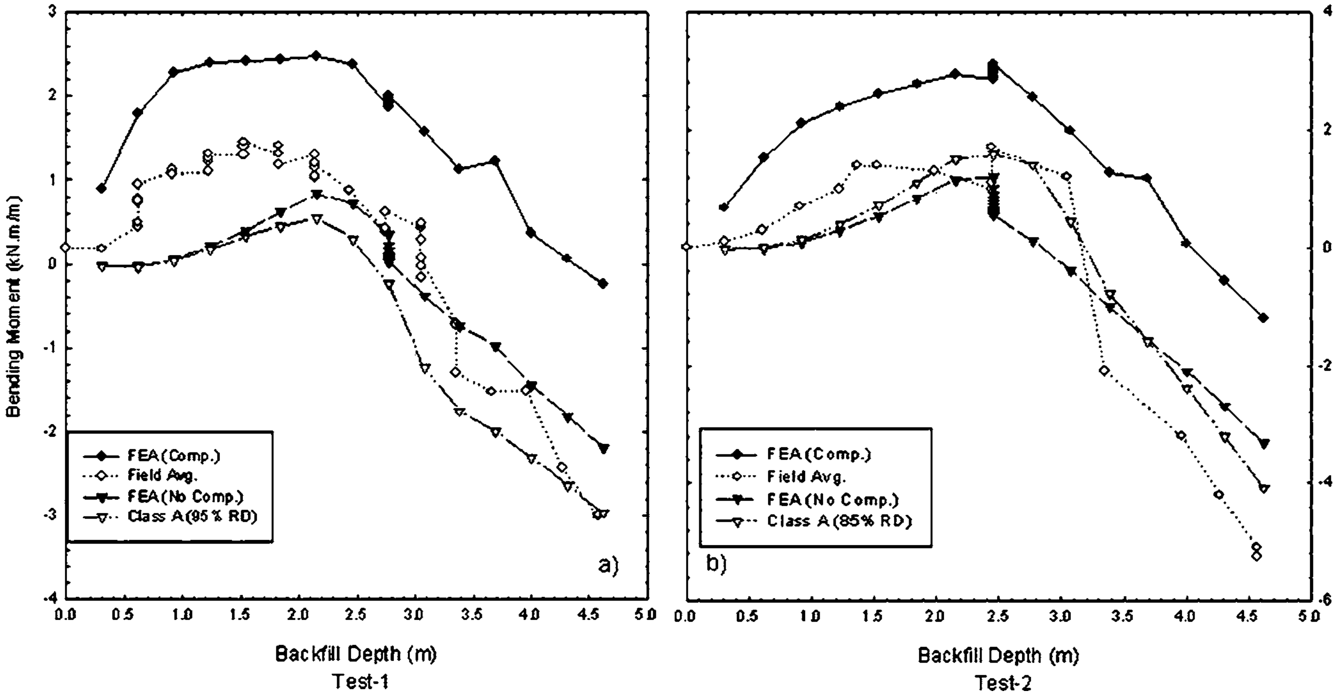


Figure 16. Crown moments: (a) Test 1, compacted; (b) Test 2, uncompacted.

TABLE 4 Response for vehicle live load: rear axles centered over crown, low-density backfill, crown values

Data Source	Load	Deflection, mm		Moment, kN-m/m		Thrust, kN/m	
		0.3 m Cover		0.3 m Cover		0.6 m Cover	
		under wheel load	2.8 m from axle centerline	under wheel load	2.8 m from axle centerline	under wheel load	at axle centerline
3D Elastic	370 kN	-22	-12	-2.1	-1.5	-180	34
2D Elastic	30 kN/m	-23		-5.7		-32	
Field Tests	370 kN	-27	-12	-1.6	-1.4	-277	38

1 kN = 225 lbs; 1 kN/m = 69 lbs/ft; 1m = 39.4 in.; 1 mm = 0.039 in.; 1 kN-m/m = 2,700 in.-lb/ft

method. This is not surprising because response to live load is a three-dimensional behavior.

Concrete Culvert Tests

Analysis of the concrete field tests focused on the interface pressures, as these pressures are commonly used as a basis for simplified design. As for the metal culvert tests, the results were evaluated with two- and three-dimensional computer models.

Table 5 compares field data with pre- and post-test calculations for earth loads. The table shows that calculated pressures at the shoulder compare well with the field data, but the calculations at the crown are less than the measurements at both locations. In this case, the field data may be in error, as the vertical pressure at the crown should be essentially geostatic, which is consistent with the computer predictions. The field data may be affected by the low cover and low stress levels.

The analysis for live-load response of the concrete culvert was made by three-dimensional finite element analysis. The quality of the calculations of radial pressures around the culvert due to live load is shown in Figures 17 and 18. These calculations indicate that the computer program accurately captured the behavior of the culvert.

Parametric Study of Metal Culvert Behavior

The parametric studies of culvert behavior are presented in detail in Appendix D. The study investigated the behavior of large-span metal culverts with spans from 4.8 to 14.3 m (15.7 to 46.9 ft) and shapes including low-profile arch, ellipse, and pear (Figure 19). Appendix D provides details of the models and results. The proposed simplified design equations are not presented here, as they are included in the proposed specifications with commentary. Key findings are summarized.

Thrust

Thrust forces in metal culverts are calculated from the magnitude of the applied loads, typically earth and live loads.

Earth loads on metal culverts were found to vary primarily with three dimensionless parameters: *W/S*, the ratio of the width of structural backfill at the side of the culvert to the span; *H/S*, the ratio of the depth of fill over the crown to the span; and *S/R*, the ratio of culvert span to culvert rise. The analysis found that the effect of these three parameters could be treated separately in terms of their effect on VAF, which is the ratio of the springline thrust in the culvert to the weight of soil directly over the crown. These are expressed as follows:

$$W_{sp} = \gamma_s (H + K_{\mathrm{VAF}} R_u) S \qquad (2)$$

$$W_E = \mathrm{VAF}\, W_{SP} \qquad (6)$$

$$\mathrm{VAF} = F_{W/S} + F_{S/R} + F_{H/S} \qquad (7)$$

where

W_{sp} = weight of soil directly over culvert, kN/m (k/ft);
γ_s = unit weight of soil, kN/m^3 (k/ft^3);
S = outside span of culvert, m (ft);
H = depth of fill over top of culvert, m (ft);
K_{VAF} = 0.172 + 0.019 × S/R_u, factor to account for curvature in top span;
= 0.21 for circular culverts;
R_u = vertical rise of culvert from point of maximum span to top of culvert, m (ft);
W_E = total earth load on culvert used in design, kN/m (k/ft);
VAF = vertical arching factor, used to account for soil-structure interaction; and
$F_{W/S}$, $F_{S/R}$, $F_{H/S}$ = factors contributing to design value for VAF.

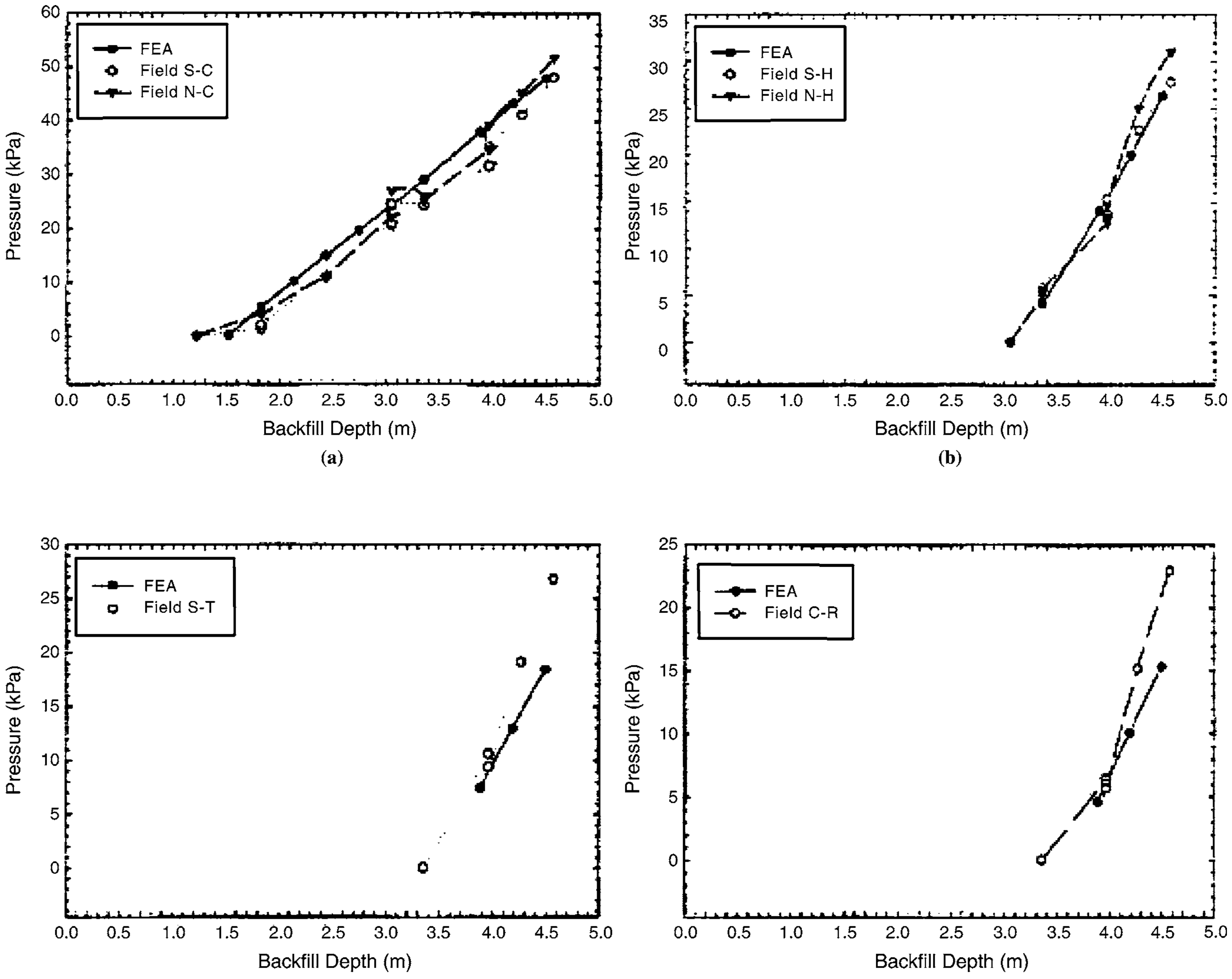
Recommended design values for VAF for typical large-span metal culverts range from about 1.1 for deeply buried culverts to 2.5 or greater for shallow-buried culverts with narrow width of structural backfill.

Live loads decay rapidly with increasing depth of fill over the culvert as the load effects spread laterally through the soil. This rate of spreading is normally accounted for by the live-load distribution factor (LLDF) multiplied by the depth of fill. The rate of this decay has been the subject of some controversy in recent years, as the LRFD specifications use a LLDF value of 1.15, whereas the earlier standard specifications used a value of 1.75. The proposed thrust calculated for large-span

TABLE 5 Pre- and post-test predictions and measurements of soil pressures due to earth loads

		Earth Pressures kPa			
		Test 1		Test 2	
		Shoulder	Crown	Shoulder	Crown
Measured	North	52	23	22	27
	South	48		11	
Calculated	Pre-Test	24		21	
	Post-Test	52	16	44	18

1 kPa = 0.14 psi



(a) (b)

(c) (d)

Figure 17. Comparison of field-measured and calculated normal earth-load soil stresses around concrete culvert during backfilling: Test 1.

metal culverts is actually larger than that calculated with either of the prior AASHTO procedures. This is because large-span culverts have large radii and develop significant thrusts at the crown, directly under the vehicle. Figure 20 presents a comparison. The proposed calculation is not recommended for other culvert sizes at this time.

Once determined, thrust forces are used to evaluate three limit states:

- Yielding,
- Seam strength, and
- General buckling capacity.

Yielding and seam strength have always been limit states for large-span culverts; however, general buckling has long been ignored, as no suitable design model existed. Buckling models for smaller culverts were known to be overly conservative when applied to large-span culverts. The proposed simplified design method incorporates the continuum model for buckling (Appendix D; Moore 1994), as it has been shown to provide designs consistent with field experience. The continuum model also incorporates features to address the reduction in buckling capacity in a buried culvert with low fill height.

Flexure

Bending moments in metal culverts are derived from three sources: earth loads, live loads, and construction loads. The limiting flexural capacity is the plastic moment capacity of the structural member, which may be made up of the structural plate and circumferential stiffeners.

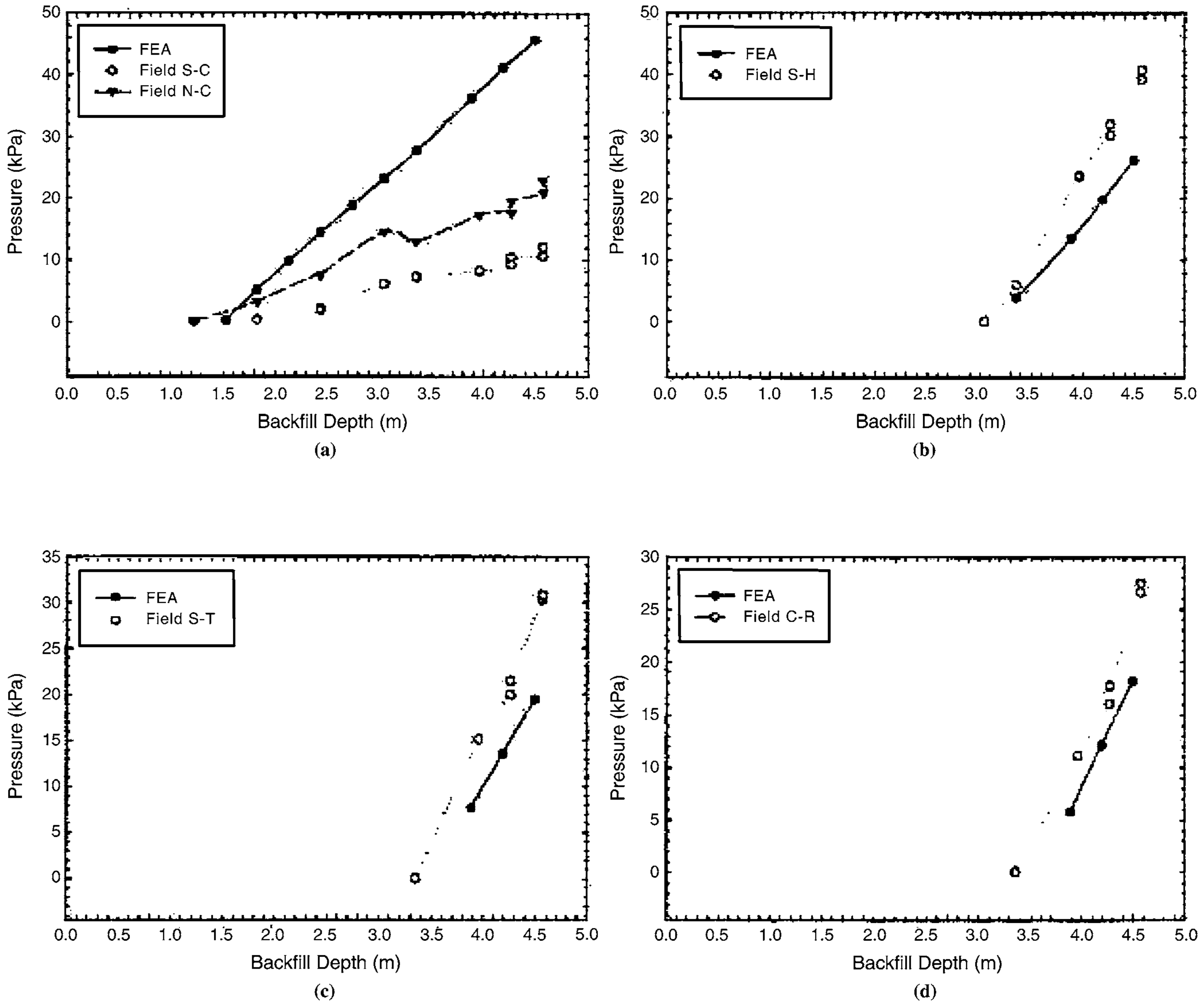


Figure 18. Comparison of field-measured and calculated normal earth-load soil stresses around concrete culvert during backfilling: Test 2.

Earth-load and live-load moment calculations for the simplified design method were derived from the parametric study. In both cases, moment is computed based on the bending stiffness parameter:

$$S_B = M_S S^3 / E_P I_P \qquad (8)$$

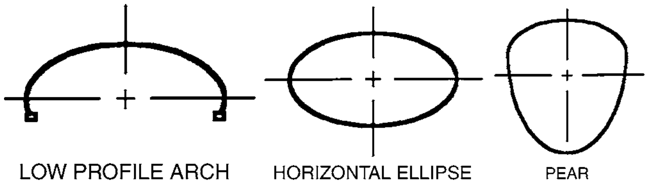


Figure 19. Metal culvert shapes considered in parametric study.

where

S_B = bending stiffness factor for the culvert-soil system;
M_S = constrained modulus of compacted backfill, evaluated at the depth of the top of the culvert for live load and at the widest part of the culvert (a greater depth) for earth load, MPa [kips/ft^2 (ksf)];
S = culvert span, m (ft);
E_P = modulus of elasticity of culvert wall material, MPa (ksf); and
I_P = average moment of inertia of stiffened culvert wall per unit length, m^4/m (ft^4/ft).

The bending stiffness parameter is used to account for the relative stiffness of culvert and soil. For many large-span culverts, parameter S_B exceeds a limiting value, resulting in the bending moment being independent of culvert properties. This

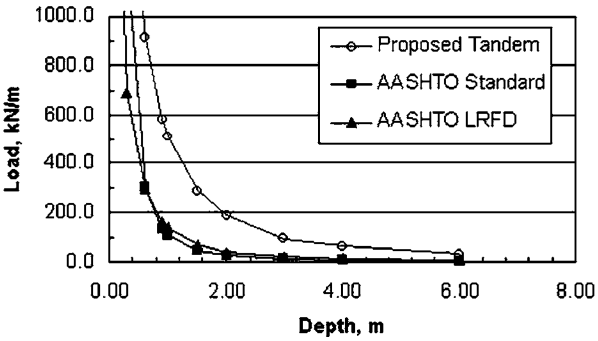


Figure 20. Comparison of proposed live-load thrust calculation with AASHTO standard and LRFD specifications.

is predicted by soil structure interaction theory (e.g., Burns and Richard 1964).

Earth-load moment—The design equation for earth-load moment is as follows:

$$M_E = \gamma_S S^2 H K_E \tag{9}$$

$$K_E = 0.05\left(1 - \frac{S_B}{S_B + 400}\right) \geq 0.0025 \tag{10}$$

The simplified expression for earth-load moment increases with depth. For designs where the earth-load coefficient K_E is controlled by the limiting value of 0.0025, the increase is linear with depth; for other designs, the increase is nonlinear and is affected only by the change in soil modulus, which in turn affects the value of S_B. This increase in moment with depth of fill suggests that deeply buried culverts will be limited by flexure, which is contrary to past practice, where deeply buried culverts are designed only for thrust. To address this, the proposed design method continues the philosophy of ignoring moment for deeply buried culverts by adding a criterion that allows design for flexure to be dropped for deeply buried culverts. Reasoning that the earth-load moment is ignored because the structure is in a stable soil environment that does not allow significant shape change and where there are no cyclic loads suggests that such a cutoff for consideration of bending moment be based in some way on the depth of fill. The proposed limit is that when the live-load moment is less than 15 percent of the total moment capacity of the section, the design criteria for ultimate flexure, and subsequently combined thrust and flexure (see below), need not be evaluated.

Live-load moments—A similar approach is taken for calculating live-load moments. Again the moments are calculated based on S_B, and the proposed design equation is as follows:

$$M_{LL} = 2W_{LL} R_t K_{LL} \tag{11}$$

$$K_{LL} = 0.02\left(1.05 - \frac{S_B}{S_B + 800}\right) \geq 0.001 \tag{12}$$

Construction moments—As discussed, it is not possible to analytically capture all the variations in construction practices that lead to moment while placing backfill at the side of a large-span culvert. Thus, the simplified design method relies on control of field deformations through the presence of a shape control inspector during construction and predicting moments based on the allowed changes in shape. In this approach, it is assumed that no axial deformation occurs, and thus the perimeter remains the same length. Using the geometry presented in Figure 21 and the following moment curvature relationship allows computation of the bending moments:

$$M = E_p I_p \left(\frac{1}{R} - \frac{1}{R_N}\right) \tag{13}$$

where

M = moment in culvert, kN-m/m (in.-k/in.);
E_p = modulus of elasticity of culvert material, kPa (ksi);
I_p = moment of inertia of pipe culvert wall, m^4/m ($in.^4$/in.);
R = radius of culvert element prior to construction, m (in.); and
R_N = radius of culvert element after backfilling to crown, m (in.).

The value of the deformed radius R_N is calculated from the following equation:

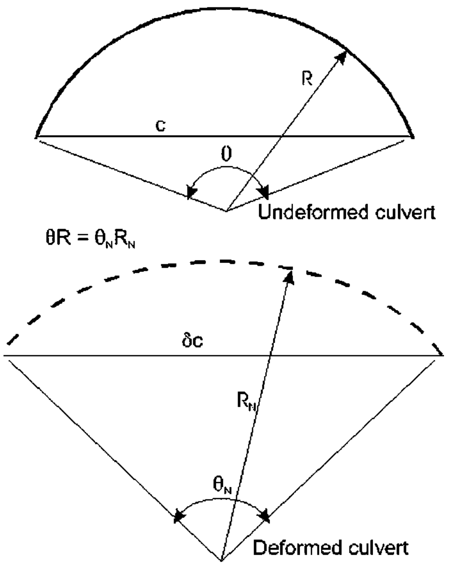


Figure 21. Deformed and undeformed culvert technology.

$$\delta c = 2R_N \sin\left(\frac{\theta R}{2R_N}\right) \tag{14}$$

where

δc = deformed chord length, m (in.); and
θ = angle of the culvert element under consideration, radians.

The term $(1/R - 1/R_N)$ represents the change in curvature of the culvert as a result of backfilling and compaction. As applied in the simplified design method, the construction moment calculation assumes that the deforming elements remain perfectly circular. This is not realistic in and of itself; however, because the plates are bolted together, the researchers believe there is likely some rotation at the seams that will not produce moment and that the procedure captures the moment due to construction deformation with sufficient accuracy for design.

Combined Thrust and Moment

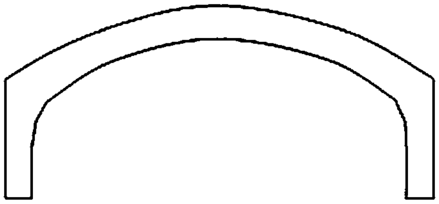
The AASHTO LRFD specifications include design equations for evaluating the capacity of steel members subject to thrust and moment. This limit is included here for large-span metal culverts under shallow cover. The combined stress criterion becomes the limiting condition for shallow-buried culverts subject to live loads; however, as noted above in the discussion on flexure, the combined stress criterion does not apply to deeply buried culverts, defined as culverts where the moment due to live load is less than 15 percent of the total moment capacity. Based on the success of past experience, deeply buried culverts will continue to be designed solely for thrust.

Parametric Study of Concrete Culvert Behavior

The parametric studies of concrete culvert behavior are presented in detail in Appendix D. The effort to investigate the behavior of concrete culverts was more limited than that for metal culverts. Included were an 11-m (36-ft) span arch culvert with a curved top slab and straight sidewalls and a 9-m (30-ft) span fully curved arch. The shapes are shown schematically in Figure 22. Long-span concrete culverts are considered to be open-bottom sections. The proposed simplified design equations are not presented here, as they are included in the proposed specifications with commentary (Appendix F of the research team's final report). Key findings are summarized.

Pressure Distributions

The main focus of the effort to understand the behavior of large-span concrete culverts was to develop standard, simplified pressure distributions that could be applied to frame models for solution of the design forces. This is the approach used in developing the SIDD method of concrete pipe design that was adopted by AASHTO some years ago.



a) Arch Top, Straight Leg Culvert

b) Arch Culvert

Figure 22. Culvert shapes in concrete parametric study.

Concrete culverts are normally designed for a uniform load distribution over the top of the culvert. The magnitude of the load varies, but, for circular shapes and embankment-type installation conditions, the load is often about 1.4 times the weight of the soil prism load (i.e., VAF = 1.4). Large-span concrete culverts tend to have a higher span/rise ratio than circular pipes, and they are typically installed at depths much lower than one times the span. This leads to changes in typical design assumptions for rigid culverts:

- Because of the long, low profile, the soil structure interaction that causes the load to increase above the weight of the soil prism tends to be concentrated at the edges of the culvert span; and
- Because of the high span/rise ratio, the magnitude of the total increase in load is less than the typical pipe value of VAF = 1.4.

The above reasoning may be evaluated by examining the vertical pressure across the top of the culvert. Figure 23 presents such a figure, using the normalized pressure as:

$$p_{\text{norm}} = p_v / (\gamma_S z) \tag{15}$$

where

p_{norm} = normalized soil pressure on culvert;
p_v = vertical soil pressure on culvert, kPa (psi);
γ_s = unit weight of soil, kN/m^3 (k/in.^{3}); and
z = depth from ground surface to top of box section, m (in.); z varies across the top of the culvert (Figure 24).

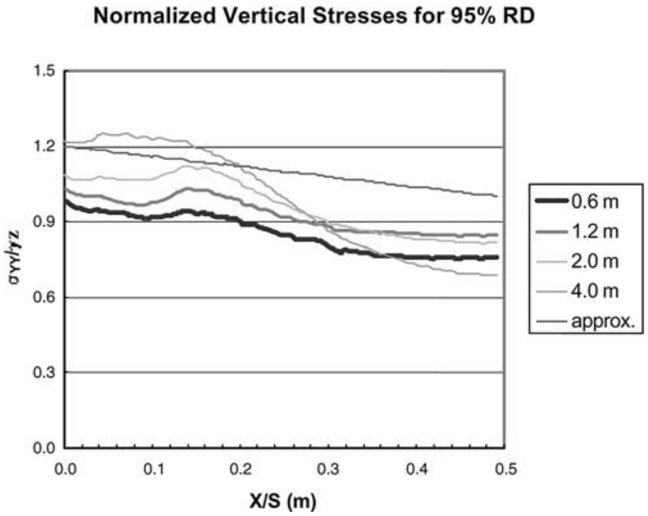


Figure 23. Vertical soil stresses on culvert normalized by depth of fill.

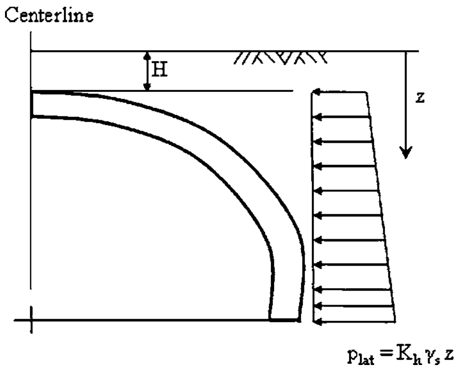


Figure 25. Horizontal pressure distribution on concrete culverts.

Figure 23 indicates that the vertical pressure on the center of the culvert should be taken as $\gamma_s z$ and that it could be assumed to vary to a value of $1.2\gamma_s z$. The complete analysis presented in Appendix D indicates that the backfill density does not significantly affect the magnitude of VAF. Thus, the simplified vertical pressure distribution can be constant for all shapes and densities. The proposed distribution on the section is shown in Figure 24. Because of the curved surface on the culvert and the variable factor on the pressure, the proposed distribution is nonlinear.

Horizontal pressures are somewhat more complex than vertical pressures, as they vary significantly with the soil density. In the parametric study, lateral soil pressures were again normalized by the free-field vertical soil stress $\gamma_s z$, thus producing a typical lateral pressure ratio, K_h. Figure 25 presents the schematic assumption for the lateral pressure distribution, and Figure 26 presents the lateral pressure ratios computed from the parametric study of the arch top, straight-sided culvert. The data indicate that the lateral pressure ratio increases with depth of cover H when the culvert is backfilled with a granular backfill at 95 percent of maximum standard Proctor density (AASHTO T99). For soils at a lower density, the lateral pressure ratio increases somewhat with depth, but that magnitude of change is reduced.

Review of the normalized horizontal pressures leads to the recommended design pressures in Table 6. The table is similar to the lateral pressures used for reinforced concrete pipe design.

For large-span culverts with curved tops and coarse-grained backfill (SW) at a density of 95 percent of maximum, the lateral pressure ratio increases with depth of fill, whereas for large-span culverts with flat tops, the ratio is constant at all depths of fill. This difference occurs because culverts with curved tops deflect outward into the backfill and develop a modest passive reaction as vertical earth load increases. The design approach does not consider large-span concrete cul-

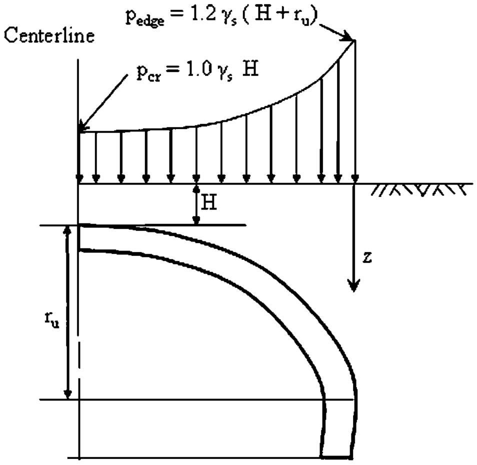


Figure 24. Simplified vertical pressure distribution on concrete culvert.

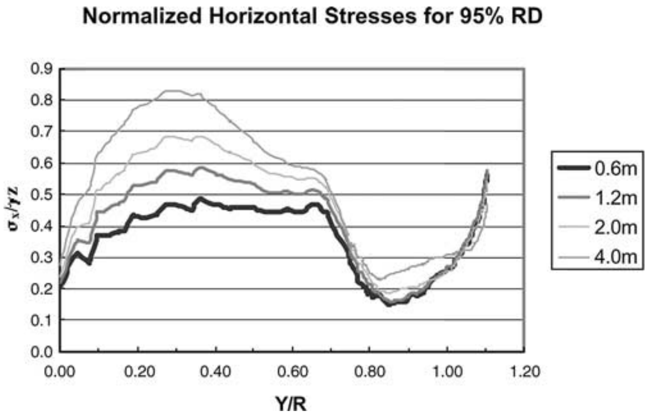


Figure 26. Normalized horizontal stresses, 95 percent density.

TABLE 6 Coefficients for simplified pressure distributions on concrete culverts

Soil Type & Compaction Level (Note 1)		K_h	
		Curved Top	Flat Top
SW	95	0.40 + 0.05 H ≤ 0.6 (H in m) 0.40 + 0.16 H ≤ 0.6 (H in ft)	0.40
SW	90	0.40 + 0.025 H ≤ 0.6 (H in m) 0.40 + 0.008 H ≤ 0.6 (H in ft)	0.40
ML	95		
SW	85	0.40	0.37
ML	90		
CL	95		
Other Soils		0.30	0.30

Note: Soil types are defined in Table 27.5.2.2-3 of the LRFD Construction Specifications, which need to be incorporated into the design specifications. Compaction levels are % of maximum density per AASHTO T99.

verts to be flexible, however, as the maximum lateral pressure ratio is limited to 0.6, whereas a typical flexible pipe might develop a lateral pressure ratio of about 1.0.

Coarse-grained structural backfill with a lower density, or other backfill material with any density, must undergo a larger strain than is possible to develop the full passive reaction.

MINIMUM STIFFNESS

With the exception of large-span metal culverts, minimum stiffness has long been an important design criterion of flexible culverts. Minimum stiffness is controlled by setting a maximum value of the flexibility factor S^2/EI. The flexibility factor has not been applied to large-span metal culverts because experience has shown that the structures can be successfully installed. Current AASHTO specifications do require that large-span culverts have either circumferential or longitudinal stiffeners, which effectively increase the stiffness to resist deformation during installation, but, because the role of these stiffeners is not defined, there was no way to include their benefit in design. The proposed specifications include procedures to consider the effect of stiffeners in the design process; thus, the flexibility factor (FF) should now be used to evaluate the minimum stiffness. The proposed criterion

$$FF \leq 0.17\text{mm}/N\ [30\ \text{in./kip(in./k)}] \tag{16}$$

imposes the current AASHTO limit for pipe arches and arches manufactured from 150 × 50 mm (6 × 2 in.) corrugated plate onto the design of large-span metal culverts. The method of determining the required flexibility factor has been broadened to include the effect of backfill type

$$\text{FF} = \frac{(2R)^2(1 - \sin\phi_{\text{loose}})^3}{0.07E_pI_p} \tag{17}$$

where

FF = flexibility factor, mm/N [in./kip (in./k)];
R = radius of the plates under consideration, mm (in.);
ϕ_{loose} = friction angle of backfill in the loose state;
E_p = modulus of elasticity of culvert material, MPa (ksi); and
I_p = moment of inertia of pipe wall, mm^4/mm ($\text{in.}^4/\text{in.}$).

Including the term $(1 - \sin\phi_{\text{loose}})^3/0.07$ requires that FF be increased for culverts installed in structural backfill with a friction angle before compaction of less than 36°. This essentially means that if the backfill has more than about 12 percent fines, the required FF is increased. The basis for including this parameter is described by McGrath et al. (1999), who found that distortion during backfilling increases as the friction angle decreases. This is a result of the increased lateral pressures generated when such backfills are compacted.

The criterion is applied to the top plates of all large-span culverts and to the side plates of high-profile large-span culverts.

Circumferential Stiffeners

Circumferential stiffeners consist of structural members mounted parallel to the culvert span. Although circumferential stiffeners are normally bolted to the structural plate, there is evidence (Byrne et al. 1997, McCavour et al. 1998) that such a connection does not provide composite action. Thus, any assumption of composite action must be demonstrated by test or by calculation. In the absence of composite action, the moment of inertia of the stiffened structure per unit length is the sum of the unit moment of inertia of the structural plate plus the moment of inertia of the stiffener divided by stiffener spacing.

Circumferential stiffeners should not be spaced more than 750 mm (30 in.) apart if designed to resist live loads after construction or 1500 mm (60 in.) apart if designed only for shape control during backfilling.

Longitudinal Stiffeners

Longitudinal stiffeners consist of continuous structural elements attached along the length of the culvert, typically at the junction of the top and side plates. Longitudinal stiffeners assist in shape control during backfilling by increasing the effective length of culvert that resists lateral forces due to backfill placement and compaction. In calculating FF, the moment of inertia of the structural plate can be increased to account for the extra longitudinal distribution of the construction forces achieved by the longitudinal stiffeners. However, no a priori assumptions are available for what this length is; thus, designers must demonstrate a basis for the assumed effective length.

Longitudinal stiffeners are not considered in design as contributing to flexural strength to resist earth, live, or construction loads.

BUCKLING

Current AASHTO specifications do not include a limit state for buckling of large-span metal culverts, as earlier design equations used for buckling of pipe are known to be conservative for larger spans. Most buried pipe design uses the Luscher (1966) equation for buckling, which is based on a pipe supported by discreet springs of uniform stiffness around the circumference. This equation has been successfully calibrated for the design of small pipe and is used by AASHTO for thermoplastic pipe design. Expressed in terms of the critical applied pressure on the exterior of the culvert, the equation takes the following form:

$$p_{\mathrm{cr}} = \frac{2(B' R_W M_S E I)^3}{R^{1.5}} \tag{18}$$

$$B' = \frac{1}{1 + 4e^{-0.21h}} \tag{19}$$

$$R_W = 1 - 0.33\frac{h_W}{h} \tag{20}$$

where

p_{cr} = critical buckling stress, MPa (psi);
B' = dimensionless nonuniform stress distribution factor;
R = pipe radius, mm (in.);
h = height of ground surface above pipe, m (ft) (for U.S. customary units the constant in the exponent of the definition of B' changes to –0.065);
R_W = water buoyancy factor;
h_W = height of water surface above pipe, m (ft);
ϕ_S = resistance factor for soil stiffness ($\phi_s = 0.9$);
M_S = constrained soil modulus, MPa (psi);
E = modulus of elasticity of culvert, MPa (psi); and
I = moment of inertia of culvert wall, mm^4/mm (in.^{4}/in.).

Moore (1994) proposed an alternative design equation based on continuum theory, where the buckling analysis is completed with the pipe uniformly or nonuniformly supported around its entire circumference, as it is in the ground. Using the approximation that the critical thrust R_b is equal to the critical pressure times the radius $p_{cr}R$, this theory can also be stated in terms of the critical applied pressure:

$$p_{\mathrm{cr}} = \frac{1.2 C_n (EI)^{1/3} (M_S K_b)^{2/3} R_h}{R} \tag{21}$$

where a factor is used to account for the nonuniformity of ground support:

$$R_h = \frac{11.4}{11 + S/H} \tag{22}$$

and other variables are defined as follows:

C_n = scalar calibration factor to account for some nonlinear effects = 0.55;
K_b = $(1 - 2\nu)/(1 - \nu)^2$, conversion term, $K_b M_s$ = plane strain modulus;
ν = Poisson's ratio of the soil; and
R = radius of a circular pipe; $S/2$ is the closest approximation for a noncircular culvert, m (in.).

The current AASHTO design equation considers pipe and soil stiffness in the term $(M_S EI)^{0.5}/R^{1.5}$, whereas the continuum theory considers the pipe stiffness with the term $(EI)^{1/3} M_S^{2/3}/R$. This formulation has the effect of decreasing the importance of pipe stiffness, increasing the importance of soil stiffness, and, perhaps most importantly, reducing the influence of the radius from $1/R^{1.5}$ to $1/R$. The latter term, which derives from the use of continuous support instead of discreet springs, results in increased predicted buckling capacity for large-span culverts.

Based on the above, the continuum buckling theory is proposed for design. Consistent with Moore's formulation of the buckling theory, the design method is expressed in terms of critical thrust R_b

$$R_b = 1.2 \phi_b C_n (EI)^{1/3} (M_S K_b)^{2/3} R_h \tag{23}$$

Additional details of the proposal for buckling design are presented in Appendix E of this report and Appendix F of the research team's final report.

CHAPTER 3

INTERPRETATION, APPRAISAL, AND APPLICATION

The primary products of this investigation are the proposed specifications for design and construction of large-span culverts included in Appendixes F and G of the research team's final report. These proposed specifications provide limit states, a simplified design model, other important design requirements, and construction guidelines for metal and concrete large-span culverts. In addition, Appendix E presents information designers need to undertake a comprehensive design of a large-span culvert and provides guidance for designers who are undertaking finite element analyses of soil-culvert interaction.

SIMPLIFIED DESIGN METHODS

The approach taken to developing simplified design methods was that current practice has no suitable design model. This is especially the case in large-span metal culverts where design for shallow fills requires only selecting a plate thickness from a table, and only a check on hoop compression is needed to complete a design for deep fills. The move to LRFD design by AASHTO requires a proper design model before accurate assessments of safety and reliability can be completed. The goal of the project, therefore, was to develop simplified design models that address all major features of culvert behavior.

Metal

The design method for large-span metal culverts is a simplified procedure that does not require any specialized computer software. The calculations can easily be completed with a spreadsheet or other calculation package, such as MathCAD.

Limit States, Load, and Resistance Factors

The design model for large-span metal culverts requires the design for the limit states presented in Table 7.

The application of limit states for flexure and combined thrust and flexure are new. Because current practice is largely experience based and does not provide a method for assessing bending moments or performance of stiffeners, it was not possible to evaluate any limit states with respect to flexure. The proposed design method provides procedures to address flexural behavior and now includes such limit states. Based on the successful past practice of designing deep large-span metal culverts only for thrust, the flexure limit state and combined thrust and flexure limit state are imposed only when there is a significant component of cyclic stress in the total flexural response. This is applied by evaluating the magnitude of the live-load bending moment relative to the plastic moment capacity of the culvert. If the moment exceeds 15 percent of the capacity, then design for flexure limit states is required.

Load and resistance factors have also been modified. On the theory that the earth loads on all types of culverts should have the same uncertainty, the earth-load factor for large-span metal culverts has been reduced from 1.95 to 1.3; however, to maintain the same overall safety, the resistance factor for thrust has been reduced from 1.0 to 0.70. New resistance factors have been introduced for bending, soil stiffness, and buckling.

Earth Load

The method proposed for computing earth load is substantially more detailed than current AASHTO specifications. The proposed method considers the shape of the culvert, width of structural backfill, and depth of fill. The resulting proposed earth loads are compared with current practice and with Duncan's (1978) proposed soil-culvert interaction method in Figure 27.

The proposed VAFs follow the same trend as those proposed by Duncan and are similar to current AASHTO values for depths of fill greater than about 0.3 times the span. The proposed method produces large VAFs for shallow fills; however, this does not significantly affect design for the following reasons:

- Factored thrust due to earth load at shallow fills is not as large as factored thrust due to live load; and
- At shallow fills, thrust due to earth load is important at the crown and shoulder where it contributes to the combined thrust and moment strength limit; the design method reduces the thrust at the crown and shoulder to 0.50 and 0.67 times the springline thrust, respectively.

Live Load

Distribution of live loads through fill is more conservative in the LRFD than in the standard specifications, because the

TABLE 7 Limit states for large-span metal culverts

Condition	Limit State
Service	Deformation (during construction and in service)
Strength	Flexure (earth, construction, and live loads)
	Thrust (yielding, seam strength, and buckling)
	Combined thrust and flexure

LLDF was reduced from 1.75 to 1.15. The LLDF is a multiplier applied to the depth of fill to account for the rate of distribution of live load with increasing depth. In simple terms, the AASHTO approach to live-load distribution is to use an equation of the following form:

$$p_{\mathrm{LL}} = \frac{P}{(\mathrm{LLDF} \times H)^2} \tag{24}$$

where

p_{LL} = live-load pressure at depth H, kPa (psi);
P = live-load magnitude, kN (lb);
LLDF = live-load distribution factor specified by AASHTO; and
H = depth of fill from top of culvert to ground surface, m (in.).

In Equation 24, the denominator is sometimes modified to add the width or length of the tire footprint. General experience in the field of geotechnical engineering indicates that the LLDF should be about 1.15 in the absence of a culvert (i.e., in an elastic half-space), and this was the basis for the change from the traditional value of 1.75 in the standard specifications. The parametric study indicates that the distribution of live load is more rapid in the presence of the culvert. For flexible culverts, this increased rate of distribution is the result of deformation of the culvert crown and increased shear stresses in the soil. To account for this, the proposed design method adopts the generalized form in Equation 25:

$$p_{\mathrm{LL}} = \frac{0.7P}{(1.15 \times H)^2} \tag{25}$$

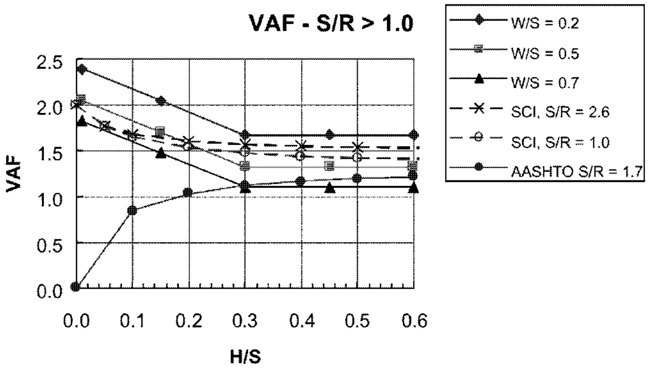


Figure 27. Comparison of proposed, current AASHTO, and Duncan VAF.

Design Method Calibration

Example calculations using the proposed design method are presented in Appendix H of the research team's final report. Additional calculations were carried out on the five culvert shapes considered in the parametric study to evaluate the performance of the design method relative to current practice. The shapes included the following:

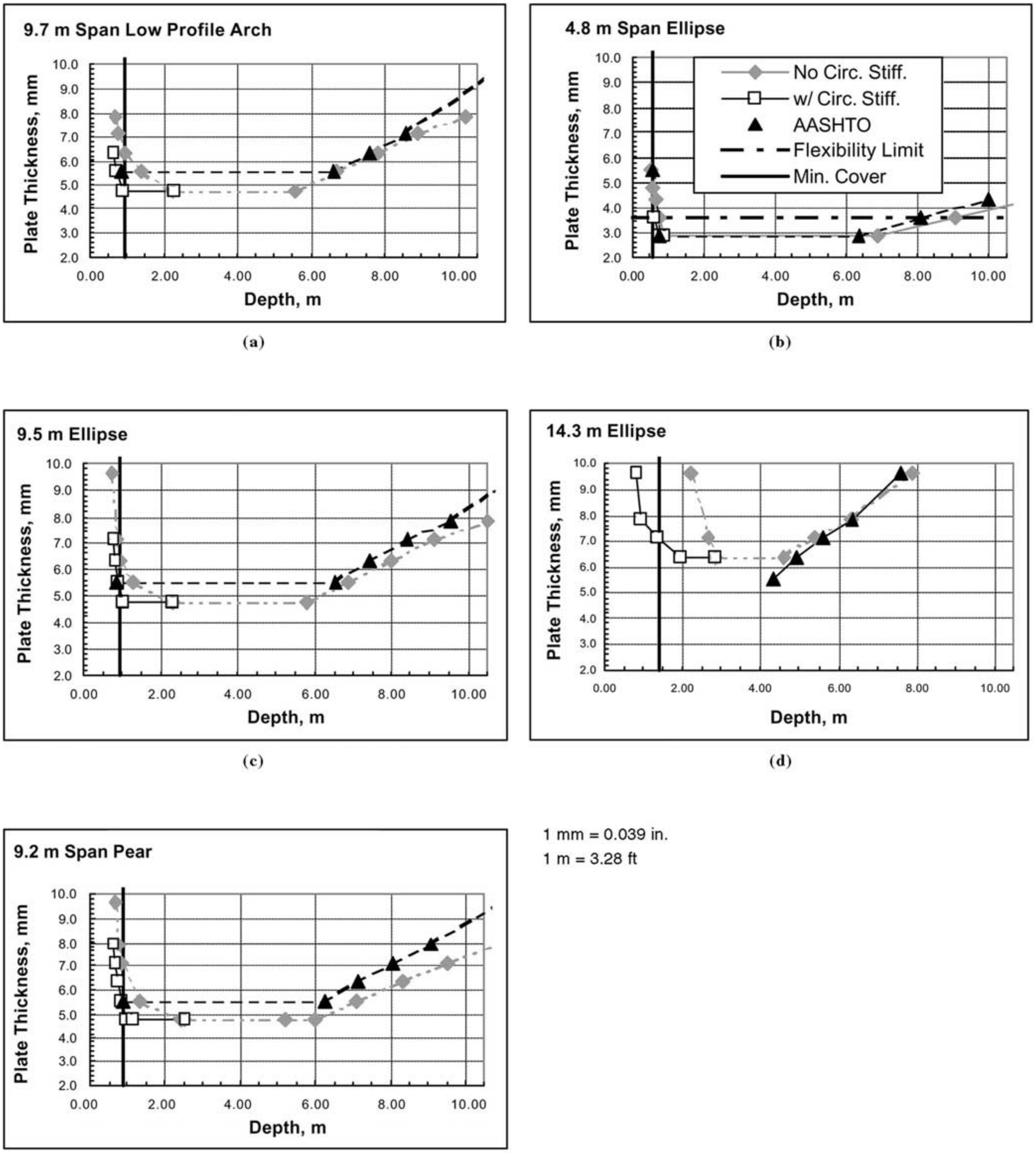
- A 9.7-m (31.8-ft) span low-profile arch,
- A 9.5-m (31.2-ft) span ellipse,
- A 4.8-m (15.7-ft) span ellipse,
- A 14.3-m (46.9-ft) span ellipse, and
- A 9.2-m (30.2-ft) span pear-shaped culvert.

Each shape was designed for depths of fill ranging from about 0.6 m (2 ft) to about 10 m (32.8 ft). All designs were assumed to meet the minimum stiffness criterion (flexibility factor), because this limit may be met by the use of longitudinal stiffeners. Of the shapes and sizes evaluated, only the 4.8-m (15.7-ft) span ellipse could have been constructed without longitudinal or circumferential stiffeners.

Figure 28 presents results of the calculations. The AASHTO designs for low depths of fill were computed with a factor of safety of 2.0 and a strength reduction factor of 1.0. This is based on the AASHTO Standard Code and is believed to be more in line with current practice than the LRFD requirement of a safety factor of 1.95 and a resistance factor of 0.67. The 14.3-m ellipse is not considered in AASHTO; thus, there is no AASHTO design for the low depths of fill in Figure 28d.

Designs with the simplified method were produced with and without circumferential stiffeners when it would affect gauge selection. Stiffeners were considered as a second structural plate of the same gauge acting with no composite action; thus, a stiffened section has twice the moment of inertia and plastic moment capacity of an unstiffened section. The use of stiffeners such as steel angles, or stiffeners that provide composite action, would change the proposed designs. In all cases, the width of structural backfill was taken as equal to the span. This effectively produces the least earth load and the lowest arching factor. All designs were also completed with granular backfill compacted to 95 percent of maximum density per AASHTO T99.

The figures indicate a generally close agreement between the AASHTO designs and the proposed design method. At intermediate depths, the proposed design method allows the sections to be one gauge thinner than design by current AASHTO. This is consistent with the findings in field tests, where a 9.7-m (32-ft) span with a 5.5-mm (0.22-in.)-thick plate performed well without circumferential or longitudinal stiffeners. However, at shallow fills, the proposed design method requires increasing plate thickness and/or stiffeners to meet the design limits. At the current AASHTO minimum thickness, the proposed design method increases the minimum depth of fill about 0.2 m (0.7 ft) for the 4.8-m (15.7-ft) ellipse and about 0.45 m (1.5 ft) for the design examples with



(a)

(b)

(c)

(d)

(e)

1 mm = 0.039 in.
1 m = 3.28 ft

Figure 28. Comparison of proposed and existing AASHTO designs.

a 9-m (30-ft) span. The calibration is very sensitive at shallow depths of fill, as the required gauge increases rapidly with decreasing depth of fill. This finding is consistent with current AASHTO designs for a 4.8-m ellipse (Figure 28b). At 0.9 m (3 ft) depth, AASHTO allows a gauge thickness of 2.82 mm (0.111 in.); yet, to reduce the depth of fill to 0.6 m (2 ft), the gauge must be increased four thicknesses to 5.54 mm (0.218 in.). At higher depths of fill, the current and proposed methods are in close agreement, which is expected. The method of calculating the earth load was modified, but no major changes were anticipated.

The assumed limits on construction deformation of the top chord can have a significant effect on design results, and different assumptions for this limit could have a significant effect on design requirements. In the design examples, we assumed the limits presented in Table 8.

Generally, a stiffened structure does not need to move as much as unstiffened structures to resist backfilling and compaction forces; therefore, the limiting deflection is reduced in some cases. Also, the smaller structures, such as the 4.8-m (15.7-ft) ellipse, will not move as much as the larger structures during backfilling. The allowable chord changes for the unstiffened structures generally permit a 2-percent increase in rise.

Concrete

The design method for large-span concrete culverts draws on the results of the parametric study for overall structural behavior and the prior research on concrete pipe (the SIDD design method adopted by AASHTO in the 1990s) for limit states and reinforcement design.

The design method for concrete culverts consists of the following:

- Computing vertical and lateral loads,
- Determining the design forces by completing a computerized frame analysis, and
- Designing the reinforcement.

Limit States and Load and Resistance Factors

Limit states for large-span concrete culverts include the service limit of cracking and the strength limits of flexure, shear, and radial tension. The reinforcement design method considers the effect of thrust as part of the evaluation of the flexure limit state. The flexure limit state is also controlled by a "maximum concrete compressive stress limit." If this limit is exceeded, it means the required reinforcement exceeds 75 percent of the balanced limit—i.e., failure may not be ductile. If this limit is exceeded, the section must be modified or designed as a column using LRFD Section 5.

TABLE 8 Allowable change in chord length used in design examples, percent

Culvert Span/Shape	Stiffened		Unstiffened	
	Max.	Min.	Max.	Min.
9.7 m Arch	0.0	-0.5	0.0	-1.0
9.5 m Ellipse	1.0	-2.0	1.0	-2.0
4.8 m Ellipse	1.0	-0.5	1.0	-0.5
14.3 m Ellipse	1.0	-1.0	1.0	-2.0
9.2 m Pear	0.0	-2.0	0.0	-2.0

1 m = 3.28 ft

Load and resistance factors for large-span concrete culverts are taken from the current AASHTO values for reinforced concrete pipe. The load factor of 1.3 for vertical earth load is the same as proposed for large-span metal culverts.

Earth Loads

Earth loads are calculated by using the VAF concept, but the value of VAF varies across the top of the culvert from 1.0 at the center to 1.2 at the edge. The net effect of the variation is that the overall VAF is about 1.15 for shallow depths of fill and reduces to about 1.10 for deep culverts. This is consistent with current practice for box sections, which are typically designed for a VAF of 1.15 if backfill at the sides of the culvert is compacted. The VAF is substantially lower than the 1.4 value typically used for reinforced concrete pipe, but this is because of the higher span/rise ratio in large-span culverts.

Live Loads

Live-load distribution through fills historically has been treated the same for metal and concrete culverts. This distribution is of the same general form as Equation 24 previously presented. Actual distribution of live loads, however, is different for flexible and rigid culverts. Analysis of data from the field tests and parametric study indicates that distribution of live loads through fill can be conservatively predicted with a LLDF of 1.15; however, after the load is applied to a rigid culvert, the distribution is further widened by the strength and stiffness of the concrete slab. This distribution is similar to the use of a strip width to estimate the width of a bridge deck that carries wheel loads. The analysis indicates that a width of 1 m (40 in.) may be used to account for this distribution. This leads to earth-load distribution of the following general form:

$$p_{\mathrm{LL}} = \frac{P}{(\mathrm{LLDF} \times H + w_{\mathrm{st}})^2} \qquad (26)$$

where

p_{LL} = live-load pressure at depth H, kPa (psi);
P = live-load magnitude, kN (lb);
LLDF = live-load distribution factor specified by AASHTO;
H = depth of fill from top of culvert to ground surface, m (in.); and

w_{st} = distribution effect due to strength and stiffness of concrete slab = 1.0 m (40 in.).

In design, the denominator is also modified by the distribution of the tire.

Calibration

Calibration to date has consisted of evaluation of three structures: a 9.1-m (30-ft) span BEBO arch culvert, and 5.4-m (16-ft) and 11-m (36-ft) span ConSpan arch culverts. The BEBO shape is the same as that tested at the University of Massachusetts, and it is curved through its entire circumference. The ConSpan shape has a curved top slab with vertical sidewalls. Details of the culverts and analysis conditions are summarized in Table 9.

Analyses were completed for the simplified method, which consisted of a frame analysis (using the computer program STAAD) and the finite element program CANDE. Results are compared with the University of Western Ontario (UWO) three-dimensional finite element method analyses where appropriate. Sample calculations are included in Appendix H of the research team's final report.

Table 10 presents a comparison of the factored thrusts, moments, and required reinforcement for the three structures by the simplified design method. Reinforcement design was completed by using the AASHTO design method for pipe sections. This provides necessary strength design criteria for flexure, radial tension, diagonal tension, and service design criteria for control of cracking.

Table 10 suggests that, for shallow depths at the crown, the reduction in live-load intensity compensates for the increased earth load, resulting in a relatively constant factored moment for depths up to about 2 m (6.5 ft). This is not the case for the negative moments that increase steadily with depth.

Table 10 shows that the 11-m (36-ft) ConSpan culvert develops substantially higher bending moments than does the 9.1-m (30-ft) BEBO culvert. This trend is partly due to the thicker section and partly due to the different shape. The ConSpan culvert has a larger radius in the top slab.

Flexure controls the reinforcement at all depths for the BEBO culvert and the 4.9-m (16-ft) ConSpan culvert. Flexure controls the reinforcement at 0.6-m (2-ft) cover for the 11-m (36-ft) ConSpan culvert; however, at depths of 1.2, 2, and 4 m (4, 6.5, and 13 ft), the criteria for diagonal tension and crack control require increases in the reinforcement area above that required for flexure. At a depth of 4 m (13 ft), the analysis indicates that shear reinforcement is required in the leg and top slab of the ConSpan culvert. The analysis is likely somewhat conservative for these conditions. Finite element analysis is less likely to produce shear forces of this magnitude.

Table 11 compares the service forces for each load condition for the BEBO and 11-m (36-ft) ConSpan arches at a depth of fill of 1.2 m (4 ft).

Tables 12–14 compare the forces from the simplified analysis with the results of the UWO study and CANDE as well as for the BEBO and 11-m ConSpan culverts. Table 12a and 12b indicates that the peak positive moments match very closely for all programs but that the error on the thrust is somewhat larger, although, because the thrust does not have a significant effect on the reinforcement design, this error is probably acceptable. Table 12c and 12d indicates that the simplified analysis predicts the negative moments and associated thrust very closely.

Table 13 indicates that the simplified analysis overpredicts live-load moments; however, this is consistent with the UWO study. At depths greater than 1.2 m (4 ft), the live-load contribution to total moment decreases rapidly.

Table 14 indicates a reasonable match between the simplified analysis and CANDE for thrust and shear at the base of the culvert leg.

COMPREHENSIVE DESIGN METHODS

The proposed design methods for incorporation into AASHTO specifications (Appendix F of the research team's final report) are based on simplifications of culvert behavior. The goal of developing the simplified procedures was to make simplifying assumptions that reduce the design process to a relatively straightforward procedure that does not require substantial experience with culverts yet accurately predicts the behavior of most common culvert sizes in common installation conditions. Use of more sophisticated procedures will generally result in more economical designs, and devel-

TABLE 9 Culvert and load conditions considered in calibration calculations

Condition	BEBO	ConSpan	
Span	9.1 m (30 ft)	11 m (36 ft)	5.4 m (16 ft)
Rise	3.7 m (12 ft)	3.4 m (11 ft)	2.4 m (7.8 ft)
Upper Rise	3.7 m (12 ft)	1.4 m (4.4 ft)	0.5 m (1.7 ft)
Thickness	250 mm (10 in.)	Arch: 300 mm (12 in.) Legs: 350 mm (14 in.)	Arch: 300 mm (10 in.) Legs: 350 mm (10 in.)
Depth of Fill	0.6 m, 1.2 m, 2 m, 4 m (2 ft, 4 ft, 6.5 ft, 13 ft)		0.6 m, 4 m (2 ft, 13 ft)
Backfill Type	SW95		SW 90
Live Load	Design Tandem		

TABLE 10 Simplified design method: factored thrusts, moments, and reinforcing requirements

a. BEBO, 9.1 m Span

Depth	Moment and Thrust (1)				Thrust at Footing	Circumferential Reinforcement Requirements				
	Peak Positive		Peak Negative			Asi	Aso			Stirrups Req'd
	M+	N+	M-	N-		Flexure	Flexure	Crack	Diag. Tens.	
m	kN-m/m	kN/m	kN-m/m	kN/m	kN/m	mm^2/m	mm^2/m	mm^2/m	mm^2/m	
0.6	107	175	87	292	306	1,020	610	DNC	DNC	No
1.2	105	218	100	350	379	930	680	DNC	DNC	No
2.0	108	277	118	438	452	890	800	DNC	DNC	No
4.0	139	452	176	686	701	1,040	1,250	DNC	DNC	No

b. ConSpan, 11 m Span (2)

Depth	Moment and Thrust (1)				Thrust at Footing	Circumferential Reinforcement Requirements				
	Peak Positive		Peak Negative			Asi	Aso			Stirrups Req'd
	M+	N+	M-	N-		Flexure	Flexure	Crack	Diag. Tens.	
m	kN-m/m	kN/m	kN-m/m	kN/m	kN/m	mm^2/m	mm^2/m	mm^2/m	mm^2/m	
0.6	185	219	393	321	321	1,500	1,650	DNC	DNC	No
1.2	197	277	484	394	409	1,540	2,050	DNC	2,941	No
2.0	219	350	608	496	511	1,690	2,620	2,900	5,080	No
4.0	311	583	968	803	803	2,710	4,510	6,180	–	Yes

c. ConSpan, 4.9 m Span

Depth	Moment and Thrust (1)				Thrust at Footing	Circumferential Reinforcement Requirements				
	Peak Positive		Peak Negative			Asi	Aso			Stirrups Req'd
	M+	N+	M-	N-		Flexure	Flexure	Crack	Diag. Tens.	
m	kN-m/m	kN/m	kN-m/m	kN/m	kN/m	mm^2/m	mm^2/m	mm^2/m	mm^2/m	
0.0	92	73	88	133	165	991	711	DNC	DNC	No
4.0	130	179	180	305	363	1,340	972	DNC	DNC	No

DNC = Does Not Control.

1. For ConSpan structure, peak negative moment occurs in the corner, where the section is thick. Outside reinforcement is always controlled at a location lower down the leg, where the section is thinner.
2. Thrust is taken at the location associated with peak moment.

1 kN-m/m = 2.70 in.-k/ft; 1 kN/m = 5.7 k/ft

TABLE 11 Comparison of BEBO and ConSpan service forces, simplified analysis at 1.2 m (4 ft) of cover

Load Condition	Manufacturer	Crown (Peak Positive)		Peak Negative (1)	
		Moment	Thrust	Moment	Thrust
		kN-m/m	kN/m	kN-m/m	kN/m
Self Weight	BEBO	8.9	18	-12.2	35
	ConSpan	18.9	29	-62.3	48
Vertical Earth	BEBO	33.0	89	-56.0	182
	ConSpan	65.6	115	-245.0	190
Horizontal Earth	BEBO	-22.2	44	32.6	1
	ConSpan	-12.2	39	28.5	15
Live Load	BEBO	33.0	26	-26.3	42
	ConSpan	44.9	32	-69.7	44
Footing Movement	BEBO	9.6	-3	4.1	-1
	ConSpan	14.8	-4	8.9	-4
Total Service Forces	BEBO	62.3	174	-57.8	260
	ConSpan	132.0	212	-340.0	292

1. "Peak negative" is the location at which the peak negative moment occurs when all load cases are combined.

TABLE 12 Comparison of simplified analysis with results from UWO three-dimensional finite element method and CANDE, ConSpan culvert, service forces

---

a. Peak Positive Moments

Depth	Peak Positive Moment			Moment Ratios	
	Simplified	3D-FEM	CANDE	Simplified/3D	Simplified/CANDE
m	kN-m/m	kN-m/m	kN-m/m		
0.6	59	60	62	0.98	0.95
1.2	87	92	89	0.94	0.98
2.0	122	128	116	0.95	1.05
4.0	209	222		0.94	

b. Thrust at Location of Peak Positive Moments

Depth	Thrust @ Peak Positive Moment			Thrust Ratios	
	Simplified	3D-FEM	CANDE	Simplified/3D	Simplified/CANDE
m	kN-m/m	kN-m/m	kN-m/m		
0.6	121	102	95.6	1.18	1.25
1.2	180	150	154.0	1.20	1.16
2.0	256	206	219.0	1.24	1.16
4.0	462	336		1.38	

c. Peak Negative Moments

Depth	Peak Positive Moment		Moment Ratios
	Simplified	CANDE	Simplified/CANDE
m	kN-m/m	kN-m/m	
0.6	-177	-176	1.01
1.2	-269	-265	1.02
2.0	-384	-360	1.07

d. Thrust at Peak Negative Moment Locations

Depth	Peak Positive Moment		Moment Ratios
	Simplified	CANDE	Simplified/CANDE
m	kN-m/m	kN-m/m	
0.6	172	163	1.05
1.2	250	247	1.01
2.0	347	344	1.01

1 kN-m/m = 2.70 in.-k/ft; 1 kN/m = 0.069 k/ft

TABLE 13 Comparison of simplified analysis with live loads results from CANDE, ConSpan culvert, service forces

---

a. Peak Positive Moment

Depth	Peak Positive Moment		Moment Ratios
	Simplified	CANDE	Simplified/CANDE
m	kN-m/m	kN-m/m	
0.6	60	48	1.25
1.2	45	36	1.26
2.0	31	22	1.41

b. Thrust at Location of Peak Positive Moment

Depth	Peak Positive Moment		Moment Ratios
	Simplified	CANDE	Simplified/CANDE
m	kN/m	kN/m	
0.6	41	47	0.88
1.2	32	28	1.16
2.0	25	19	1.31

1 kN-m/m = 2.70 in.-k/ft; 1 kN/m = 0.069 k/ft

TABLE 14 Comparison of thrust and shear at base of leg: culvert weight, earth loads, and footing movement, ConSpan culvert

Depth	Base Thrust			Base Shear		
	Simplified	CANDE	Simplified/CANDE	Simplified	CANDE	Simplified/CANDE
m	kN-m/m	kN-m/m		kN-m/m	kN-m/m	
0.6	236	232	1.02	94	67	1.40
1.2	301	318	0.95	123	101	1.22
2.0	382	417	0.92	158	131	1.21

1 kN-m/m = 2.70 in.-k/ft; 1 kN/m = 0.069 k/ft

opment of the simplified procedures should not prevent designers from using more detailed procedures when appropriate. In general, "more sophisticated procedures" means using finite element analysis to determine the design forces, followed by design in accordance with the specifications in Appendix F of the research team's final report.

Appendix E presents guidance for designers in applying finite element analysis to culvert design problems. Specific features that may be considered in a comprehensive analysis include the following:

- Nonlinear soil behavior,
- Plastic soil behavior,
- Nonlinear culvert behavior (e.g., yielding),
- Varying culvert-soil interface conditions,
- Nonuniform thrust forces around metal culverts,
- Varying construction sequences,
- Nonuniform native soil conditions, and
- Varying effects of native soil conditions and trench width.

Appendix E also provides guidance on mesh design and on computing equivalent line or strip loads to represent live loads in two-dimensional analysis.

Many software programs are available for finite element analysis. CANDE is currently the most widely available program and was developed specifically for analyzing culverts. CANDE is in the public domain and has built-in soil models suitable for culvert analysis. The Duncan et al. (1980) hyperbolic Young's modulus with the Selig (1988) hyperbolic bulk modulus currently is the most suitable soil model in CANDE. Further, the properties developed by Selig (1988) are recommended as the most suitable values for routine design. CANDE also considers nonlinear culvert behavior. However, CANDE is becoming outdated as it operates only in a DOS environment and is not interactive. CANDE should be upgraded. Other commercial finite element software, such as ABAQUS (1998), can also be used to complete analyses of large-span culverts. ABAQUS can model soil as elastoplastic with the Mohr-Coulomb failure criterion.

CONSTRUCTION SPECIFICATIONS

Controlling construction of large-span culverts, particularly metal culverts, is perhaps the most important key to achieving good performance. It has been long established that large-span culverts are susceptible to significant deformations as a result of construction practices. Appendix A of the research team's final report lists a significant number of culvert failures that resulted from poor practices. For the case of metal culverts, construction practices are so important that current AASHTO specifications require that a shape control inspector be present on site during backfilling. This requirement is continued in the proposed specifications resulting from this project. Appendix G of the research team's final report presents draft construction specifications for large-span metal and concrete culverts. Because of the importance of construction practices, these specifications are far more detailed than current specifications. Among the important procedures that have been incorporated are the following:

- Limitation of backfills consisting of uniform fine sands,
- Incorporation of controlled low-strength material as backfill,
- Detailed procedures for important steps in excavation and backfilling long-span culverts,
- Improvement in consistency across different types of culverts,
- Improvement in terminology and definitions, and
- Requirement for post-construction inspection.

Perhaps the most important feature of the specifications is that they address the backfill around the culvert as a part of the structure. As a soil-structure system, both the soil and culvert contribute to the final structural performance.

CHAPTER 4

CONCLUSIONS

NCHRP Project 12-45, *Recommended Specifications for Large-Span Culverts*, has completed a thorough evaluation of the state of the art in the design and construction of large-span reinforced concrete and metal culverts, investigated culvert behavior through full-scale field tests and extensive computer modeling, and developed recommended specifications for design and construction.

This evaluation indicates that current practice produces safe, reliable structures; however, much of the success is believed to result from experience, as the current design procedures are not specific and leave many important structural details unspecified. The current procedures for metal culverts in particular are largely empirical and do not address several key aspects of design, such as the role of stiffeners or the evaluation of moments that develop during construction or in shallow-buried structures subject to live load. Current practice for concrete culverts is more defined than for metal culverts, but some key areas are still not addressed, such as the vertical load to be used in design. This evaluation also demonstrated the importance of following correct construction procedures, as a number of failures of large-span culverts have been attributed to poor control during construction. The review of current practice showed a definite need for improved specifications.

The key element of the project was to develop two new design models for large-span culverts: (1) a simplified procedure that would accurately model most culvert installations and be suitable for incorporation into AASHTO specifications and (2) a comprehensive procedure that could be used for unusual installation or design conditions. The method used to develop these procedures was as follows:

- Full-scale field tests to develop data on culvert behavior during construction and under shallow fills subject to live loads,
- Calibration of computer models with the field data,
- Parametric studies of culvert behavior with the calibrated computer models,
- Development of simplified design equations based on parametric study results, and
- Calibration and fine-tuning of the simplified design method by applying the simplified design procedures to a range of culvert types and sizes.

Comparison with current practice was the primary means of assessing the proposed procedures, and the calibration work indicates that the proposed design procedures produce results consistent with current practice. Modifications to current design practice for metal culverts include the following:

- Addition of a service limit state for deformation;
- Incorporation of flexibility factors to large-span culverts;
- Addition of strength limit states for flexure, combined thrust and flexure, and general buckling;
- Definition of the structural role of longitudinal and circumferential stiffeners;
- Development of more comprehensive procedures to evaluate earth load; and
- Development of procedures to compute moments due to construction, earth, and live loads.

Modifications to current design practice for large-span concrete culverts include the following:

- Addition of limit state for radial tension,
- New procedures to determine earth load,
- New simplified pressure distributions for design by frame analysis, and
- Requirement that reinforcement for large-span culverts be designed according to the reinforced concrete pipe procedures.

Detailed design examples are provided to demonstrate application of the procedures for both metal and concrete culverts.

The development of simplified procedures is not meant to prevent the use of more sophisticated methods of analysis, such as the finite element method. The power of computer analysis with the finite element method is an important design tool; however, finite element analysis does require experience. Guidelines are provided for those who wish to undertake culvert design by finite element analysis. CANDE was developed for the analysis and design of culverts. It is the recommended software for designers who are new to finite element analysis and who want to focus on analysis of culvert installations. However, CANDE does need to be upgraded in the near future to take advantage of current computational power.

Construction specifications have also been developed. These specifications provide considerably more detail about the construction process than was previously available to field personnel. New aspects of the construction specifications include the following:

- Limitation on use of backfills consisting of uniform fine sands,
- Incorporation of controlled low-strength material as backfill,
- Detailed procedures for important steps in excavation and backfilling long-span culverts,
- Improvement in consistency across different types of culverts,
- Improvement in terminology and definitions, and
- Requirement for post-construction inspection.

Overall, completion of this project represents a significant step forward for the design of large-span culverts. Designers and constructors will have greatly improved tools available for designing and building these important components of our highway infrastructure.

REFERENCES

Note: References cited in the body of the report and the appendixes are listed herein.

AASHTO, *AASHTO LRFD Bridge Design Specifications,* 1st ed., Washington, DC (1994).

AASHTO, *Standard Specifications for Highway Bridges,* 16th ed., Washington, DC (1996).

AASHTO, *AASHTO LRFD Bridge Design Specifications,* 2nd ed., Washington, DC (1998).

ABAQUS, version 5.8. *Finite Element Program,* Providence, RI, Hibbitt, Karlsson, and Sorensen, Inc. (1998).

Abdel-Sayed, G., Bakht, B., and Jaeger, L. G., *Soil-Steel Bridges: Design and Construction,* New York, McGraw-Hill (1993) 359 pp.

Ansourian, P., "Structural Aspects of Steel Silos and Tanks." *Lecture 5: Non-Axisymmetric Behaviour, Unbalanced Loading,* Sydney, Australia, School of Civil and Mining Engineering, The University of Sydney (1981).

AWWA, *AWWA Manual M45, Fiberglass Pipe Design Manual,* Denver, CO (1995).

Bathe, K. J. and Bolourchi, S., "A Geometric and Material Non-Linear Plates and Shell Element." *Computers and Structures,* Vol. 11 (1980) pp. 23–48.

Burns, J. Q. and Richard, R. M., "Attenuation of Stresses for Buried Cylinders." *Proceedings of Symposium on Soil-Structured Interaction,* ASTM, University of Arizona, Tucson, AZ (1964) pp. 379–392.

Byrne, P. M., Anderson, D. L., and Ahmadi, M. M., *Failure of the Dumont Culvert,* Victoria, British Columbia, Canada, Prepared for Ministry of Transportation and Highways, Vancouver Island Highway and Project Management Team (1997).

Carter, J. P., *PROGRAM AFENA: A General Finite Element Algorithm,* Sydney, Australia, School of Civil and Mining Engineering, The University of Sydney (1992).

Duncan, J. M., "Soil-Culvert Interaction Method for Design of Metal Culverts." *Transportation Research Record 678,* Washington, DC, TRB, National Research Council (1978) pp. 53–58.

Duncan, J. M., "Behaviour and Design of Long-Span Metal Culverts." *Journal of Geotechnical Engineering,* Vol. 105, No. GT3 (1979) pp. 399–418.

Duncan, J. M., Byrne, P., Wong, K. S., and Mabry, P., *Strength, Stress-Strain and Bulk Modulus Parameters for Finite Element Analysis of Stresses and Movements in Soil Masses,* Report UCB/GT/80-01, Berkeley, CA, Department of Civil Engineering, University of California, (Aug. 1980).

El Sawy, K., Moore, I. D., and Taleb, B., "Analysis of Stability Limit States for Long-Span Culverts." *50th Canadian Geotechnical Conference,* Ottawa, Canada, Canadian Geotechnical Society (1997) pp. 178–184.

Haggag, A. A., *Structural Backfill Design for Corrugated-Metal Buried Structures,* Ph.D. dissertation, Amherst, University of Massachusetts (1989).

Heger, F. J., and McGrath, T. J., *Design Method for Reinforced Concrete Pipe and Box Sections,* Vienna, VA, Prepared for the Technical Committee of the American Concrete Pipe Association (1982).

Hoeg, K., "Stresses Against Underground Structural Cylinders." *Journal of the Soil Mechanics Division,* Vol. 94, No. 4 (1968) pp. 833–858.

Howard, A. K., "Modulus of Soil Reaction Values for Buried Flexible Pipe." *Journal of Geotechnical Engineering,* Vol. 103, No. GT1 (1977) pp. 33–43.

Janbu, N., "Soil Compressibility As Determined By Oedometer and Triaxial Test." *Proceedings of the European Conference on Soil Mechanics and Foundation Engineering* (1963) pp. 19–25.

Katona, M. G., "Analysis of Long-Span Culverts by the Finite Element Method." *Transportation Research Record 678,* Washington, DC, TRB, National Research Council (1978) pp. 59–66.

Katona, M. G. and Smith, J. M., *CANDE User Manual,* Report FHWA-RD-77-6, Port Hueneme, CA, U.S. Naval Civil Engineering Laboratory (1976).

Kay, J. N. and Abel, J. F., "A Design Approach for Circular Buried Conduits." *International Conference on Finite Elements,* Sydney, Australia (1976).

LaFave, J. M., "Large Span Precast Concrete Culvert Field Tests—Material Characterization, Crack Summary and Strain Gage Results." *NCHRP Project 12-45: Limit States Design for Long Span Culverts,* Amherst, University of Massachusetts (1998).

Leonhardt, G., "Die Erdlasten be Uberschutteten Durchlassen." *Die Bautechunik,* Vol. 56, No. 11 (1979) pp. 361–368.

Luscher, U., "Buckling of Soil-Surrounded Tubes." *Journal of Soil Mechanics Foundation Division, Proceedings of the American Society of Civil Engineers,* Vol. 92, No. SM6 (Nov. 1966) pp. 211–2218.

Marston, A. and Anderson, A. O., "The Theory of Loads on Pipes in Ditches and Tests on Cement and Clay Drain." *Tile and Sewer Pipe* (1913) p. 31.

McCavour, T. C., Byrne, P. M., and Morrison, T. D., "Long-Span Reinforced Steel Box Culverts." *Transportation Research Record 1624,* Washington, DC, TRB, National Research Council (1998) pp. 184–195.

McGrath, T. J., "Replacing E′ with the Constrained Modulus in Buried Pipe Design." *Pipelines in the Constructed Environment,* J. P. Castronovo and J. A. Clark, Eds., Reston, VA, American Society of Civil Engineers (1998).

McGrath, T. J., Selig, E. T., Webb, M. C., and Zoladz, G. V., "Pipe Interaction with the Backfill Envelope." *Publication FHWA-RD-98-191,* McLean, VA, U.S. Department of Transportation, FHWA (June 1999).

Moore, I. D., *The Stability of Buried Tubes,* PhD thesis, Sydney, Australia, School of Civil and Mining Engineering, The University of Sydney (1985).

Moore, I. D., "The elastic stability of shallow buried tubes." *Geotechnique,* Vol. 37, No. 2 (1987) pp. 151–161.

Moore, I. D., "Static Response of Deeply Buried Elliptical Tubes." *Journal of Geotechnical Engineering,* Vol. 114, No. 6 (1988) pp. 672–687.

Moore, I. D., “Three Dimensional Response of a Shallow Buried Metal Culvert.” *4th Int. Conf. on Short and Medium Span Bridges,* Halifax, Nova Scotia, Canada (1994) pp. 95–105.

Moore, I. D., “Culverts and Buried Pipelines.” *Geotechnical and Geoenvironmental Handbook,* R. K. Rowe, Ed., Boston, MA, Kluwer Academic Publishers Group (2000) pp. 541–568.

Moore, I. D. and Brachman, R. W. I., “Three Dimensional Analysis of Flexible Circular Culverts.” *Journal of Geotechnical Engineering,* Vol. 120, No. GT10 (1994) pp. 1829–1844.

Moore, I. D. and Taleb, B., “Metal Culvert Response to Live Loading—Performance of Three-Dimensional Analysis.” *Transportation Research Record 1656,* Washington, DC, TRB, National Research Council (1999) pp. 37–44.

Moore, I. D., Haggag, A., and Selig, E. T., “Buckling Strength of Flexible Cylinders with Nonuniform Elastic Support.” *International Journal of Solids and Structures,* Vol. 31, No. 22 (1994) pp. 3041–3058.

Moore, I. D., Taleb, B, and El Sawy, K., “Class A Predictions for Long Span Test Culverts.” *NCHRP Project 12-45,* London, Canada, Geotechnical Research Centre, The University of Western Ontario (1997).

Musser, S. C., *CANDE-89 User Manual,* Report FHWA-RD-89-169, Washington, DC, FHWA (1989).

Ontario Highway Bridge Design Code, Ontario, Canada, Ministry of Transportation, Downsview, Ontario, Canada (1991).

Rotter, J. M. and Jumikis, P. T., “Non-Linear Strain Displacement Relations for Axi-Symmetric Thin Shells.” *Research Report R563,* Sydney, Australia, School of Civil and Mining Engineering, The University of Sydney (1988).

Seed, R. B. and Duncan, J. M., “Soil-Structure Interaction Effects of Compaction-Induced Stresses and Deflections.” *UCB/GT/80-01, Geotechnical Engineering Report,* Berkeley, CA, University of California (1983).

Selig, E. T., “Soil Parameters for Design of Buried Pipelines.” *Pipeline Infrastructure—Proceedings of the Conference,* New York, American Society of Civil Engineers (1988) pp. 99–116.

Selig, E. T., “Soil Properties for Plastic Pipe Installations.” G. S. Buczala and M. J. Cassidy, Eds., *Buried Plastic Pipe Technology,* Special Technical Publication 1093, ASTM, Philadelphia (1990) pp. 141–158.

Selig, E. T., Abel, J. F., Kulhawy, F. H., and Falby, W. E., *Review of the Design and Construction of Long-Span Corrugated-Metal, Buried Conduits,* Report No. FHWA-RD-77-131, Washington, DC, FHWA (1977).

Spangler, M. G., “Stresses in Pressure Pipelines and Protective Casing Pipes.” *Journal of Structural Engineering,* Vol. 82, paper 1054 (1956) 33 pp.

Sussmann, J., Webb, M. C., and Selig, E. T., “Soil Properties for the Large-Span Culvert Study.” *NCHRP Project 12-45,* Amherst, MA, Department of Civil and Environmental Engineering, University of Massachusetts (1998).

Taleb, B., *Behaviour of Large-Span Culverts Under Earth and Live Loadings,* PhD thesis, London, Canada, Faculty of Engineering Science, The University of Western Ontario (2000).

Taleb, B. and Moore, I. D., “Metal Culvert Response to Earth Loading—Performance of Two-Dimensional Analysis.” *Transportation Research Record 1656,* Washington, DC, TRB, National Research Council (1999) pp. 25–36.

Webb, M. C., *Improved Design and Construction of Large-Span Culverts,* PhD dissertation, Amherst, University of Massachusetts (1998).

Webb, M. C., Selig, E. T., and Sussmann, J., “Large Span Culvert Field Test Results.” *NCHRP Project 12-45,* Amherst, Department of Civil and Environmental Engineering, University of Massachusetts (1998).

Webb, M. C., Selig, E. T., and McGrath, T. J., “Instrumentation for Monitoring Large-Span Culverts.” G. N. Durham and W. A. Marr, Eds., *Field Instrumentation for Soil and Rock,* ASTM STP 1358, American Society for Testing and Materials, West Conshohocken, PA (1999).

White, H. L. and Layer, J. P., “The Corrugated Metal Conduit as a Compression Ring.” *Proceedings of the Highway Research Board,* Vol. 39 (1960) pp. 389–397.

APPENDIX A

UNPUBLISHED MATERIAL

Appendixes A, F, G, and H as submitted by the research agency in the final report are not published herein. For a limited time, they are available for loan on request to the NCHRP. Their titles are as follows:

Appendix A: State-of-the-Art of Large-Span Culvert Design and Construction Practice
Appendix F: Proposed Design Specifications and Commentary for Large-Span Culverts
Appendix G: Proposed Construction Specifications and Commentary for Large-Span Culverts
Appendix H: Example Calculations with Simplified Design Procedures