

Current Practice of Reinforced Concrete Box Culvert Design

MAHER K. TADROS, CONSTANCE BELINA, AND DALLAS W. MEYER

Although the state of Nebraska alone spends about \$2.50 million annually on construction of reinforced concrete box culverts, relatively little research has been devoted to them in recent years. The research described in this paper was, in part, directed at establishing the state of the art of the design of these culverts. Specifically, a summary is given in this paper of the results of recent field measurements. It has been found that the field measurements of soil pressures indicated higher pressures than those given by the American Association of State Highway and Transportation Officials specifications. The responses of state bridge engineers, or those with similar responsibilities, to a questionnaire on their design practices are reported herein. Several inconsistencies in the American Association of State Highway and Transportation Officials specifications were reported. Despite these inconsistencies and the apparent underestimation of soil loading, very little structural distress was observed. Lack of distress may be attributed to several causes. For example, some of the states use higher soil pressures than American Association of State Highway and Transportation Officials' specified values. Also, the conservative criteria associated with the working stress design increase the margin of safety against failure and reduce the effect of underestimating the soil loads.

Use of cast-in-place reinforced concrete box culverts (RCBCs) as underground conduits is common throughout the United States. In the state of Nebraska the Department of Roads currently spends about \$2.6 million on RCBC construction annually. Typical design of the RCBC within the United States is based on the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges (1). Soil loads are usually based on the AASHTO Group X loading for culverts.

Relevant full-scale testing by previous investigators is summarized herein. This testing has indicated a substantial discrepancy between the AASHTO design loads and in situ measured values. Because of these discrepancies, a survey was taken of the various state highway departments to determine their design practices. The topics addressed in the survey included the design method, load factors, soil loadings, and any structural distress encountered.

A discussion of the results of the survey is presented herein. The various practices are compared with the AASHTO specifications. It is shown that some of the states have recognized recent experimental and analytical evidence that the AASHTO specifications generally underestimate soil pressures on RCBCs.

The survey also indicates that a number of the states have

adopted the load factor design approach as opposed to the older, and generally more conservative, service load design method. It is interesting to note that very few cases of structural distress were reported in the survey. Reasons for this apparently good performance, despite the use of relatively small loads in design, are discussed herein.

The subject of this paper is primarily the current design practices of cast-in-place RCBC. Recent analytical work (2) has indicated the need for critical review of the AASHTO specified soil pressures on RCBCs. The work was done with the aid of the computer program CANDE (3, 4). Discussion of that work is beyond the scope of this paper.

Excellent work on precast concrete box culverts has recently been conducted by Heger et al. (5-7), Boring et al. (8), and LaTona et al. (9). This work confirms that soil pressures specified in Sections 3 and 6 of the AASHTO bridge specifications are lower than those obtained from field measurements and from rigorous soil-structure interaction analysis. LaTona et al. (9) discuss the computer program that led to ASTM C789 and C850 standard specifications for precast reinforced concrete box sections (10, 11).

SURVEY OF STATE HIGHWAY DEPARTMENTS

In July 1984, bridge engineers, or those with similar responsibilities in all 50 state highway departments, received a letter that requested data on the concrete box culvert design practices used in their respective states. A copy of this letter is given in Figure 1. Thirty responses were received by letter or by telephone. Some responses were very brief; others, however, discussed their design practice in some detail. Remarks from several states included copies of design manuals for box culvert design. A synthesis of the information received is shown in Table 1. The following is a summary of the responses to the five questions asked in the letter.

Design Method

At the time they responded to the survey, 10 states used the load factor design (LFD) method. Twenty states used the service load design (SLD) method; however, 7 of the 20 use LFD for certain cases, as explained in the table.

Load Factors

In general, states that used either design method applied load factors in accordance with the 1983 AASHTO Standard Spec-

M. K. Tadros and D. W. Meyer, University of Nebraska-Lincoln, 60th and Dodge Streets, Omaha, Nebr. 68182-0178. C. Belina, 812 Leawood Drive, Omaha, Nebr. 68154.



Address All Replies To:
Department of Civil Engineering
60th & Dodge Streets
Omaha, Nebraska 68182-0178

We are presently conducting research on the design of reinforced concrete box culverts for the Nebraska Department of Roads and the Federal Highway Administration. Finite element modeling of the culverts and the surrounding soil has indicated to us that the soil loads specified by the current AASHTO Bridge Specs are probably too low. Our analysis indicates a vertical soil pressure in excess of the AASHTO value of $(0.7) \times (120 \text{ pcf}) \times (\text{fill height})$. Our analysis also indicates that the lateral pressure of $(30 \text{ pcf}) \times (\text{soil depth})$ specified by AASHTO is probably too low.

The comparisons we have made so far are analytical, using the computer program "CANDE." As you probably know, this comprehensive program was primarily developed by Notre Dame University for the FHWA.

The only recent experimental results available to us on box culverts at this time are those reported by Kentucky during the 70's. Settlements and soil pressures were measured on a 4ft X 4ft single cell box with a 77ft. fill. Their results indicate higher soil pressures than AASHTO specified values.

We are wondering whether your state has conducted studies of loads on box culverts, in particular, or of design of these culverts, in general. Results of experimental work would be most helpful. We would also like to know the procedures and design philosophy followed in your state. For example, (1) Do you use the strength or the working stress design method? (2) What load factors are assigned to soil and live loads, if any? (3) Do you design for soil loads that differ from the AASHTO Specs? On what basis? (4) Do you specify Grade 40 or Grade 60 steel? (5) Have your box culverts experienced any consistent form of distress or excessive deformation?

Your time and effort in responding to this request will be most appreciated. If you would like to discuss this matter further, or transmit your response by telephone, please call me collect at (402) 554-3286.

Sincerely,

Maher K. Tadros

FIGURE 1 Questionnaire sent to state departments of transportation.

ifications for Highway Bridges and subsequent interims. In the AASHTO specifications, RCBC are categorized into the AASHTO Group X loadings. The equation for Group X loading is

$$\text{AASHTO Group X} = \gamma[\beta_D D + \beta_L (L + I) + \beta_E E]$$

For SLD, $\gamma = 1.0$, $\beta_D = 1.0$, $\beta_L = 1.0$, $\beta_E = 0.7$ for vertical and 1.0 for lateral loads on RCBC. If the reinforced concrete box culvert is designed as a rigid frame, $\beta_E = 0.5$ or 1.0 for lateral loads, depending on which one controls.

For LFD, $\gamma = 1.3$, $\beta_D = 1.0$, $\beta_L = 1.67$, and $\beta_E = 1.0$ for vertical loads. Again, $\beta_E = 0.5$ or 1.3 for lateral loads, depending on which one controls. Several states, however, used a modified version of the AASHTO Group X loads, as shown in Table 1.

Comments from three states, South Dakota, Washington,

and Virginia, indicated that they prohibit the reduction of vertical soil pressure to 70 percent of the actual load, as allowed by AASHTO for SLD. The chief structural engineer from South Dakota commented that his department felt that the β_E coefficients specified by AASHTO for LFD were too low because soil pressures on reinforced concrete box culverts are less predictable than are dead loads. The Virginia chief engineer's comments reflected the feeling that soil bridging may not exist over new reinforced concrete boxes. Washington reported experience with negative arching, that is, loads on the culvert that are greater than the weight of the soil prism above the box.

Several states indicated that the 0.7 reduction factor applied to vertical soil pressure in the AASHTO service load method was never intended to account for the effect of soil arching. Rather, the purpose of the 0.7 factor was to effect an increase

TABLE 1 SURVEY OF HIGHWAY DEPARTMENT RESPONSES

State	Design Method Used ^a	Load Factors	Design Vertical Soil Loading, lb/ft ³	Design Horizontal Soil Loading, ^b lb/ft ³	Reinforcement Grade Specified
Arizona	SLD	AASHTO Group X	120	30	See ^c
California	LFD	$(\gamma\beta_D/\phi) = (\gamma\beta_E/\phi) = 1.5$ $(\gamma\beta_L/\phi) = 2.5$	140	42 or 140	60
Connecticut	SLD ^d	AASHTO Group X	120	30	60
Idaho	SLD	—	—	45 or field test	40
Illinois	LFD	$\gamma = 1.5$ for $D + E$ $\gamma = 1.3$ for $L + I$ $\beta_E = 1.3$ for lateral E and 0.5 for checking + M in slabs	120	40 for fill height 50 for barrel height	60
Iowa	LFD	AASHTO Group X	140	36	40
Kentucky	LFD	AASHTO Group X	120	34–45	60
Maine	LFD	$\beta_E = 1.3$	—	36	60
Michigan ^e	LFD	$\gamma = 1.3$ for $D +$ vertical E $\gamma = 1.69$ for horizontal E	120	15 or 30	60
Minnesota	LFD	—	—	75%, 33%, 16.5% of vertical pressure	60
Mississippi	SLD	AASHTO Group X	120	30	40
Missouri	SLD ^f	AASHTO Group X	120	30	60
Montana ^g	—	—	—	—	—
Nebraska	SLD	AASHTO Group X	120	15 or 30	40
New Hampshire	SLD	AASHTO Group X	120	Varies with fill height H : 15 or 45 for $H < 30$ ft 15 or 60 for $30 \text{ ft} < H < 60$ ft 30 or 90 for $60 \text{ ft} < H < 90$ ft	60
New Jersey	SLD	AASHTO Group X	120	35	60 ^h
New York	SLD	AASHTO Group X	120	30	60
North Carolina	LFD	AASHTO Group I	120	30	60
North Dakota	LFD	—	120	40	60
Oklahoma	SLD ⁱ	AASHTO Group X	120	36	40
Oregon	SLD	—	—	—	60
Rhode Island	SLD ^d	—	—	35	60
South Carolina	SLD	AASHTO Group X	120	30	40 ^j
South Dakota	SLD ^d	$\beta_E = 1.0$ for vertical soil pressure	120	20 or 40	60
Tennessee	SLD ^k	AASHTO Group X	120	30	60
Texas	SLD ^l	—	120	20 or 40	See ^l
Virginia	SLD ^d	$\beta_E = 1.0$ for vertical soil pressure	—	—	40 ^j
Washington	SLD	$\beta_E = 1.0$ for vertical soil pressure	130	15 or 60	40 ^j
West Virginia	SLD	AASHTO Group X	120	30	40
Wyoming	LFD	AASHTO Group X	120	36	60

^a LFD = Load Factor Design, SLD = Service Load Design.

^b Equivalent Fluid Pressure.

^c Arizona specifies grade 40 for bar sizes #6 and smaller and grade 60 for bars larger than #6.

^d Precast concrete culverts are designed by LFD.

^e SLD is used for 3-cell boxes.

^f Triple boxes and special conditions are designed by LFD. Eventually all design will be by LFD.

^g No recent experience with RCBCs.

^h Contractor may submit an alternate design using grade 40 reinforcing.

ⁱ LFD is used to check strength in special cases.

^j Grade 60 reinforcing may be substituted for grade 40.

^k Tennessee has discussed changing to LFD.

^l LFD has been used for special cases with grade 60 steel only when needed.

in the allowable stress under dead load, as compared with that allowed under live load. The same explanation for the reduction factor has been reported in the literature [see, for example, work by Davis and Bacher (12)].

Soil Loading

At the time of the survey, AASHTO specifications recommended the use of a vertical soil pressure of 120 lb/ft³ and a horizontal soil pressure of 30 lb/ft³ equivalent fluid pressure

for the design of reinforced concrete box culverts. Eleven states, out of those who supplied information on soil pressures used in design, indicated use of the AASHTO loads without modification. Three states used values other than 120 lb/ft³ for vertical soil loads. Eighteen states reported the use of horizontal soil pressures different from AASHTO values.

Several states specified minimum and maximum values of horizontal soil pressure, apparently to conform to AASHTO Section 3.20.2., which requires that only one-half of the bending moment caused by lateral soil pressure may be used to reduce positive moment in the slabs. California required

equivalent fluid densities of 42 and 140 lb/ft³ to be used in design. The former loading is based on a drained embankment condition, whereas the latter represents a saturated soil condition.

Structural Materials

In the LFD method, the computed ultimate structural strength is highly dependent on the strength of the reinforcing steel. This question was addressed in the questionnaire with most states reporting the use of grade 60 reinforcing bars. Some states specified grade 40 but allowed the use of grade 60 reinforcing.

Structural Distress

In general, the states responding to the questionnaire have had good experience with reinforced concrete box culverts, with few instances of structural distress reported. Three states reported some cracking, which was attributed to differential settlement. One state experienced cracking in the positive moment areas of the top slab under higher fill heights. Another

state reported cracking in the positive moment zone of the bottom slab of a culvert, under which it was suspected that swelling of the bedding material had occurred.

It should be pointed out that the negative moments at the corners of RBCBs are generally higher than the positive moments at the center of the spans. Thus, cracking is on the side adjacent to the soil where it cannot be easily observed. This cracking is perhaps more serious in terms of corrosion of the reinforcing steel.

Studies done at the University of Nebraska (2) show that the service load design method, when applied to RBCBs, produces designs with excessive factors of safety against failure. The underestimation of soil loads appears to be offset by this excessive factor of safety.

FIELD TEST DATA

Four groups of researchers have conducted projects, which have included observations of soil pressures on reinforced concrete culverts. The Kentucky Department of Transportation has compiled data from one pipe culvert location and seven box culvert installations, four with the imperfect trench and three without (13-16). The imperfect trench method of

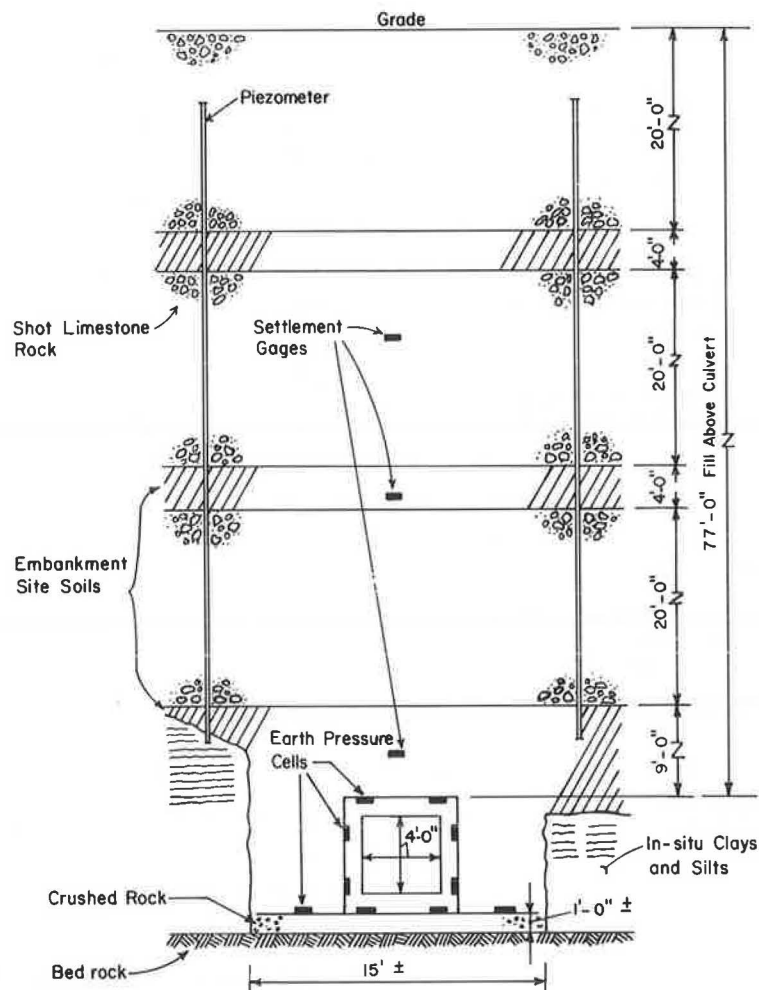


FIGURE 2 Field instrumentation, 4- by 4-ft box culvert (77-ft fill), Station 123+95, Clark County, Kentucky.

culvert construction involves the excavation of a trench in the embankment above the culvert. The trench is filled to some height with loose material, such as soil or baled straw, and is then covered with normally compacted embankment material. Only projects constructed without the imperfect trench condition are discussed. The three box culverts constructed without the imperfect trench had dimensions that varied from 4 ft by 4 ft to 6 ft by 6 ft. Fill heights varied from 37.5 ft on a 5 ft by 4 ft culvert to 77 ft on the 4 ft by 4 ft culvert.

Figure 2 is shown to illustrate the testing configuration for the 4-ft by 4-ft culvert with 77 ft of fill. Figures 3, 4, and 5 illustrate the test results compared with the AASHTO Group X loadings for the 4 by 4-, 5 by 4-, and 6 by 6-ft boxes, with normal pressure, lb/in².

A recent study funded by the Texas Highway Department and the Federal Highway Administration (17) involved instrumentation of one reinforced concrete box culvert. Soil pressure readings were taken at fill heights varying from 8 in. to 8 ft. This research focused on evaluation of the soil-culvert system under both backfill and live loads.

A research team from Northwestern University has instrumented two 60-in.-diameter reinforced concrete pipe culverts, one in the embankment condition and one in a trench condition (18–20). In the embankment case, the culvert was founded on natural ground and approximately 25 ft of embankment material was placed around it on both sides and on top. For the other case, a deep and narrow trench was dug in natural

soil; the culvert was placed in the trench and covered with fill material to approximately 30 ft.

The California Department of Transportation has conducted a research project that included measurements of soil pressures under imperfect trench conditions. Three of the structures tested were reinforced concrete arches including a 10-ft arch with 200 ft of fill, an 8-ft arch with 240 ft of fill, and a 22-ft arch with 190 ft of fill. Two 84-in. diameter reinforced concrete pipes were instrumented at two locations, with fill heights of 136 ft and 183 ft. A 96-in. prestressed concrete pipe with 200 ft of fill was also tested. (21–29).

SUMMARY OF FIELD TESTS

Several observations can be made about the research projects mentioned in this paper that relate to reinforced concrete box culverts. For all projects, regardless of culvert shape, the soil-pressure versus time curves are approximately linear. That is, from the beginning of construction to the time of fill completion, soil pressures were observed to be proportional to fill height. In addition, a substantial amount of soil friction on the side walls was observed in all of the RCBC projects. This friction generally exhibited a downward drag, thus increasing the pressures on the bottom slab.

After fill completion, however, changes in soil pressure with time varied among the projects. For most of the pipe and arch structures, vertical soil pressures changed only negligibly with time; horizontal pressures, however, did increase with time, especially at the California sites. An exception to this is the twin pipe installation in Kentucky in which vertical pressures increased with time while horizontal pressures remained fairly constant. On two of the box culverts in Kentucky, soil pressures increased significantly after fill completion, by about 25 percent. It should be pointed out that measurements were taken on the Kentucky boxes for more than 2,000 days. This is about twice as long as the period of time for which measurements have been reported for the other installations.

Loads resulting from horizontal and vertical soil pressure were not symmetrical about the culvert vertical centerline at any of the field installations. The amount of asymmetry varied among the different projects, however, and may be related to the asymmetry of the in situ geologic conditions at the individual sites. The Texas researchers believed that the asymmetry of pressure cell readings could be attributed to uneven fill compaction at the low fill heights involved or the questionable reliability of the pressure cells at these low pressures.

Both horizontal and vertical soil pressures were higher than AASHTO design loads at the Kentucky box culvert locations and at the Ohio embankment pipe installation. Observed pressures were lower than AASHTO loads at the Kentucky pipe culvert site and at the Ohio trench pipe location. At the Texas box culvert site, horizontal pressures were higher and the vertical pressures were lower than AASHTO loads at low fill heights. The California research in general showed higher vertical pressures on the arches and lower vertical pressures on the pipes when compared with AASHTO values. For both arches and pipes, observed horizontal soil pressures at the California locations generally fell between the two AASHTO-

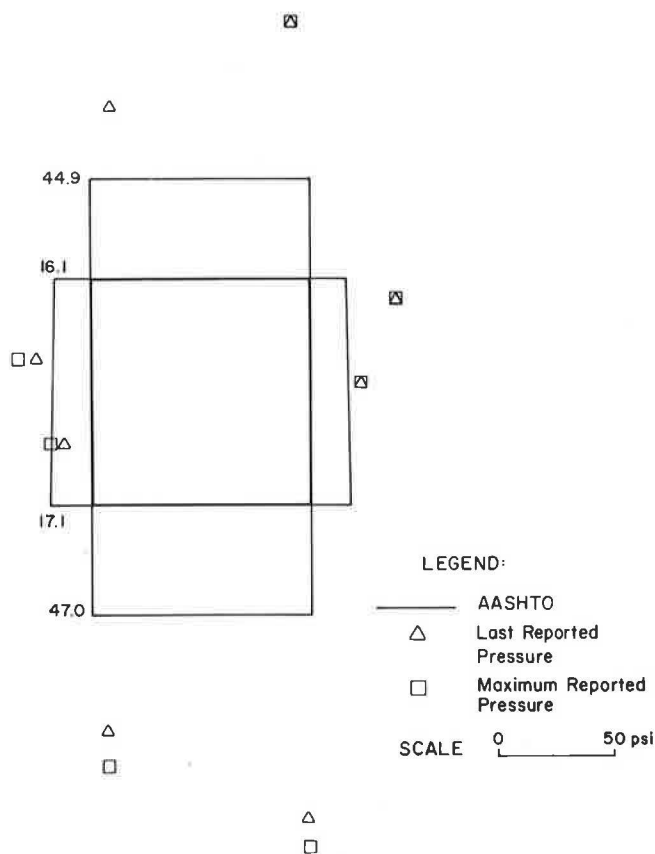


FIGURE 3 Comparison of test and AASHTO results: 4- by 4-ft box culvert (77-ft fill), yielding foundation, Station 123+95, Clark County, Kentucky.

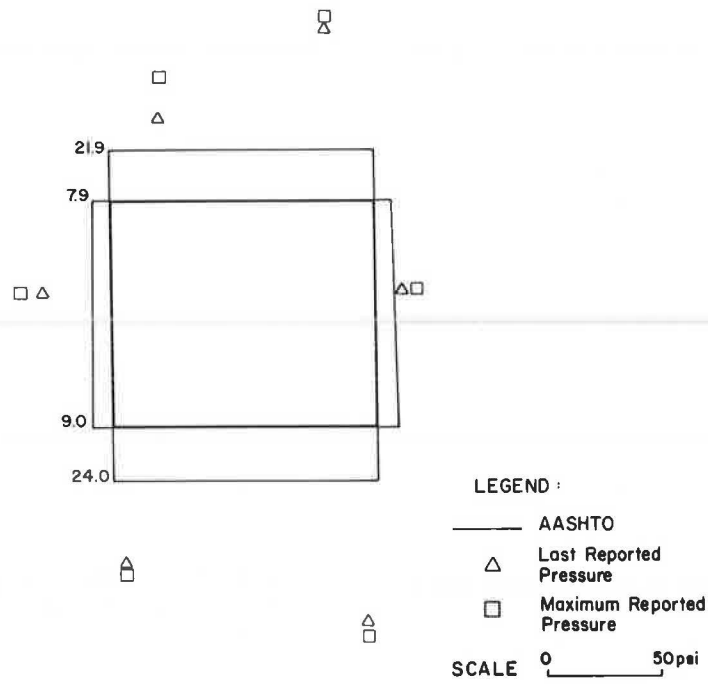


FIGURE 4 Comparison of test and AASHTO results: 5- by 4-ft box culvert (37.5-ft fill), unyielding foundation, Station 268 + 30, Clark County, Kentucky.

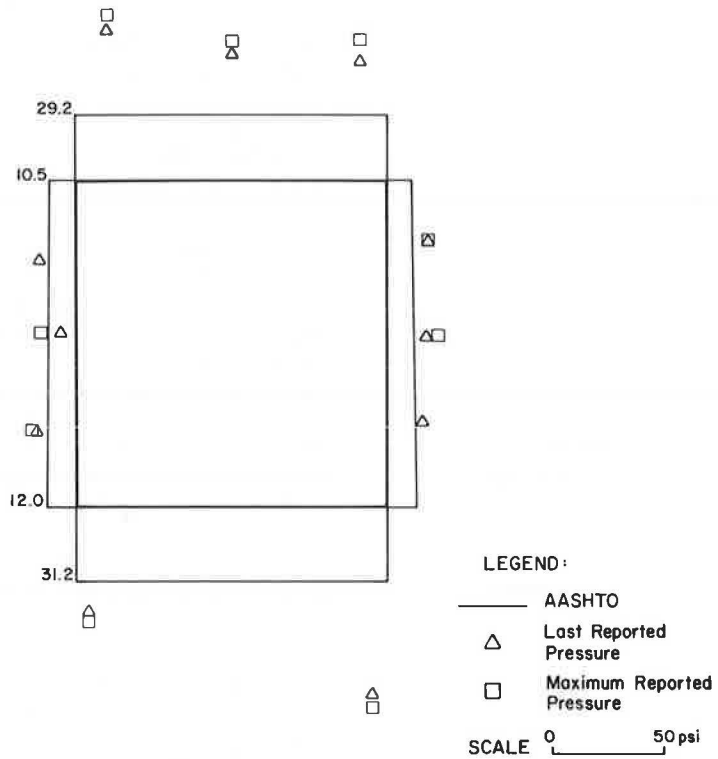


FIGURE 5 Comparison of test and AASHTO results: 6- by 6-ft box culvert (50-ft fill), Station 459 + 50, Marion County, Kentucky.

specified design loads of 30 lb/ft³ and 120 lb/ft³ equivalent fluid pressure.

CONCLUSIONS

The survey of state highway departments has indicated a diverse interpretation and application of AASHTO specifications relevant to concrete box culvert design. A number of states use higher soil pressures than AASHTO-specified values. Also, there appears to be a trend toward more use of the strength design approach. Only a few cases of structural distress were reported, indicating that current design practices produce safe, but not necessarily economical, box culverts.

Field measurements of culvert behavior have been limited. Most of the testing on pipe culverts was performed in California. Kentucky's work was done on seven box culverts, mostly under deep soil fills. The test program in Texas was somewhat inconclusive. Additional field research would provide a larger data base to compare experimental results with correct design procedures. Any improvement in the culvert design procedures could result in safe, yet more economical, structures.

The analytical work done at the University of Nebraska (2) seems to support this belief. That comprehensive study addressed soil pressure distribution, live load distribution, and influence of the design methods used. Research is currently underway to obtain field measurement on a twin cell 12-ft by 12-ft box culvert with 12 ft of soil fill. A report on these field measurements and comparison with analytical values will be given at a later date.

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