Soil-Structure Analysis and Evaluation of Buried Box-Culvert Designs

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Precast reinforced-concrete box culverts are relatively new products in culvert technology. Currently, the most widely used design procedure is ASTM C789 (Specifications on Precast Reinforced Concrete Box Sections for Culverts, Storm Drains and Sewers). These ASTM design tables give maximum allowable earth-cover heights for standard box sizes and steel reinforcement, determined by a linear-elastic frame analysis of the box section with an assumed soil pressure loading. No consideration is given to soil stiffness or soil-structure interaction. In this study, the final objective is to evaluate the structural adequacy of the ASTM box designs by using the finite-element program Culvert Analysis and Design (CANDE), which includes nonlinear elements for reinforced concrete, incremental soil construction, and fully automated mesh-generation schemes for culvert applications. To this end, the CANDE reinforced-concrete box model is validated with experimental data from out-of-ground box culverts loaded to ultimate. Next, the CANDE box-soil model is validated with experimental data from an in-ground box-culvert test with incremented soil loading. After the CANDE box-soil model has been validated, it is used to evaluate the ASTM box designs with regard to the 0.01-in crack-width limitation and the load factor for ultimate failure. In general it is concluded that the ASTM box designs are conservative but not uniformly conservative and the effect of soil stiffness is significant.

Precast reinforced-concrete box culverts as opposed to cast-in-place box culverts are relatively recent additions in culvert technology; they have come into popular use within the last decade. Design guidelines for precast reinforced-concrete box culverts (hereafter called simply "box culverts") are provided by ASTM C789-79 and AASHTO M259-76I for earth covers more than 2 ft. Both the ASTM and the AASHTO box-culvert design tables, which are essentially identical, are based on linear-elastic frame analysis of the box cross section with an assumed soil-pressure distribution. Design heights of earth cover, box wall thicknesses, and reinforcing steel areas are determined by ultimate strength design criteria and 0.01-in crack-width limitations. Soil-structure interaction is not taken into account.

Although these design tables are commonly used in practice, the design and analysis method and assumptions have not been experimentally verified for in-ground conditions. Nor has the design been cross-checked with analytical procedures employing soil-structure interaction together with the nonlinear nature of reinforced concrete. The latter leads to the objective of this study.

By using a finite-element analysis procedure [Culvert Analysis and Design (CANDE)] for modeling the nonlinear behavior of box culverts along with the soil system, the objectives are (a) to validate the finite-element box-culvert model with experimental data from out-of-ground box tests loaded to failure in four-edge bearing, (b) to validate the combined box-soil finite-element model with experimental data from an in-ground box-culvert test with incremental soil loading, and (c) to evaluate the ASTM C789 buried box-culvert designs with the finite-element model, i.e., determine earth-cover heights that produce 0.01-in crack widths and cover heights that result in ultimate box failure in flexure or shear.

This box-culvert study is part of a larger buried-culvert research program that has been sponsored by the Federal Highway Administration and has been going on for several years. The major product of the research program is the finite-element program CANDE (1-4), which is used here for the objectives given above. Other applications of CANDE are cited in reports by Katona (5-9).

CANDE MODEL AND BOX-CULVERT CRITERIA

CANDE Program

CANDE is a special-purpose finite-element program primarily intended for the design and analysis of buried culverts. Because of the generality afforded by the finite-element solution methodology, a variety of other soil-structure interaction problems can also be analyzed, such as underground storage facilities, retaining walls, embankments, and tunnels.

Some useful features of the program include incremental construction to model the physical process of constructing soil structures in a progressive manner, linear and nonlinear soil models, nonlinear beam-rod elements to model yielding and cracking of structural components (e.g., reinforced concrete), and frictional interfaces (e.g., between soil and structure) to simulate frictional sliding, debonding, and rebonding during the loading schedule. Also, the program is equipped with completely automated mesh-generation schemes for culvert applications.

The scope of the program is limited to plane strain geometry and loading, real-time independence, and small-deformation theory. In particular for the case of a buried box culvert, a plane strain slice of the culvert cross section is modeled with a series of connected beam-rod elements, and the soil system is modeled with nonconforming, four-node quadrilateral elements in a plane strain formulation. Typically, the soil system contains three soil zones--in situ soil, bedding, and fill soil, where the fill soil is incremented into the system in a series of soil lifts that mimicks the actual construction process and provides a history of structural responses. For the purposes of this article, a brief overview of the reinforced-concrete beam-rod element is given along with the criteria used for predicting concrete crack widths and ultimate failure. Complete details, as well as details of other modeling assumptions (e.g., soil models, friction interfaces, and incremental construction), are given in CANDE documentation manuals (1-4).

Reinforced-Concrete Element

A reinforced-concrete element, whether it is part of a culvert or of any structural system, poses a difficult analysis problem due to the nonlinear material behavior of concrete in compression, cracking of concrete in tension, yielding of the reinforcement steel, and the composite interaction of concrete and reinforcement. Matters are complicated further when the internal moment, shear, and thrust at a particular cross section are not proportional (including load reversals) during the loading history. Such is the case for buried box culverts during the installation process.

To cope with these problems, the following geometric and kinematic assumptions are employed in the CANDE beam-rod element: (a) displacements and strains are small, (b) transverse planes remain plane and normal, and (c) the steel reinforcement

Figure 1. Idealized concrete stress-strain behavior.

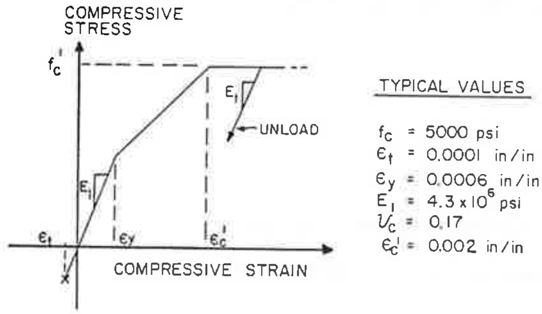
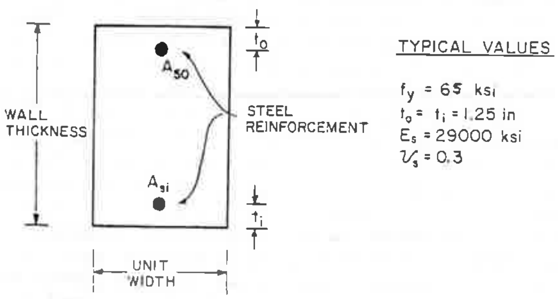


Figure 2. Steel reinforcement in concrete wall.



remains bonded to the concrete.

With regard to material behavior, the stress-strain behavior for concrete is represented by the trilinear curve shown in Figure 1 where the curve is defined (input) by the strain measures ε_t, ε_y, and ε_c' along with the initial modulus E_1 and strength f_c'. In compression, the concrete is linear elastic up to the initial yield strain ε_y. Between ε_y and ε_c' the response is plastic with hardening, and beyond ε_c' the response is perfectly plastic. Unloading from compression is elastic as shown. In tension, the concrete is linear up to ε_t (cracking strain). Cracked concrete is assumed stress-free so that pre-cracked stresses are redistributed. Once a particular location in the beam cross section has cracked, the tensile strength of that location is set to zero; this infers that the cracks do not heal.

The stress-strain relation for reinforcing steel is assumed elastic and perfectly plastic, defined (input) by the elastic modulus E_s and yield stress f_y, taken identical in compression and tension, and unloading is elastic. Reinforcing steel is considered to be lumped near the top and bottom of the cross section located by concrete cover thicknesses (input) as indicated in Figure 2. Since the concrete cross section is of unit width (plane strain slice), the steel areas A_s are the bar areas divided by the spacing.

By using the above assumptions, the beam-rod element is developed from a displacement formulation based on incremental virtual work wherein standard two-point hermitian interpolation functions are used to approximate transverse displacement increments, and linear interpolation functions are used for axial-displacement increments. This results in a tangent element stiffness matrix corresponding to 6 degrees of freedom, two translations, and a rotation (increments) per node. Effective bending and axial stiffness terms in the element matrix are determined iteratively during each load step by using 11-point Simpson integration through the element cross section. That is, the strain profile at the end of the load step is used to recompute the stiffness terms, and the load step is repeated until convergence of all elements is observed.

Criteria for Crack Widths and Failure

Once a converged solution has been obtained for a reinforced-concrete culvert model under service loading, structural distress may be assessed by (a) maximum tensile steel stress, (b) maximum concrete compressive stress, (c) maximum concrete shear stress, and (d) maximum concrete crack width. The first three measures of distress are obtained directly from the structural response predictions of the CANDE model. Crack-width prediction, however, requires a semiempirical approach. An empirical formula relating crack widths to maximum tensile steel stress is given by Gergely and Lutz (10):

$$C_w = 0.000\,15(t_b^2 S)^{1/3}(f_s - 5.0) \tag{1}$$

where

C_w = crack width at tension steel (in),
t_b = concrete cover to steel center (in),
S = spacing of reinforcement (in), and
f_s = tensile steel stress (ksi).

The above formula was found to give good predictions for crack widths in this study and is further supported by other studies involving one-way slabs with deformed wire, deformed wire fabric, and deformed bars (11). For culvert installations, it is generally accepted that crack widths should be no larger than 0.01 in under service loading (ASTM C789-79 and AASHTO M259-76I).

When loading becomes excessive, failure of the reinforced-concrete beam-rod element occurs in either of two ways--flexure or shear. Flexure failure (actually flexure-thrust failure) occurs when the cross section cannot sustain any additional loading; i.e., all uncracked concrete is at maximum compressive strength f_c' and all steel reinforcement is yielding. Typically this infers flexural cracks, plastic hinging of steel reinforcement, and crushing of concrete.

Shear failure, characterized by diagonal cracking, is determined by a standard American Concrete Institute (ACI) strength definition (12). Specifically, shear failure of an element is said to occur when the predicted nominal shear stress is equal to the concrete shear strength; i.e.,

$$V/A_c = 2(f_c')^{1/2} \tag{2}$$

where V is the predicted shear force, A_c is the concrete area between the steel reinforcement, and $2(f_c')^{1/2}$ is the shear strength (f_c' is in psi units).

For a reinforced-concrete culvert (e.g., box or pipe) composed of an assemblage of elements, ultimate flexural failure (including thrust interaction) occurs when a sufficient number of elements fail in flexure (plastic hinges), which produces a collapse mechanism. However, ultimate shear failure of the culvert structure is said to occur when any single element fails in shear. These ultimate failure criteria were found to correlate well with experimental data for box and pipe culverts loaded in bearing.

VERIFICATION OF CANDE MODEL WITH EXPERIMENTAL DATA

To demonstrate the validity of the CANDE culvert model, comparisons are made with experimental data for (a) out-of-ground box culverts loaded in four-edge bearing and (b) an in-ground box culvert with incremented soil loading.

Out-of-Ground Box Tests

These experimental data were obtained from a testing program (13,14) for reinforced-concrete box culverts with welded wire fabric reinforcement loaded to failure in four-edge bearing as indicated in Figure 3. Three box sizes were tested, each with three amounts of steel reinforcement--low, medium, and high. Thus, nine separate box designs were tested; there were two repeated tests per box design (18 tests). Table 1 (13,14) lists these boxes along with measured values for concrete strength (including repeated box tests), steel areas (corresponding to those in Figure 3), and measured steel strength. Experimental data from the test program include the load at which 0.01-in cracking occurs and the ultimate load in shear or flexure, to be compared subsequently with the CANDE model predictions (load-deformation curves were not measured during the experiments).

Figure 4 shows the finite-element model for a typical box-culvert test where, because of symmetry, only half the box is modeled by using 14 elements. Each element cross section is assigned the concrete thickness, steel area, steel location, and steel strength as actually reported from the experimental tests. For the concrete material properties, f_c' is taken as given in Table 1 so that repeated tests are also analyzed. The other concrete model parameters are assigned the standard values noted in Figure 1.

Figure 5 shows the comparison between test data and CANDE predictions for the load P per foot length of box that produces the first occurrence of an 0.01-in crack. These cracks occur on the inside surfaces of the top and/or bottom slabs near the centerline. Overall, a reasonably good correlation is observed; predicted load values average 10 percent lower than test results.

When the test boxes were loaded to ultimate, 10 tests failed in flexure and 8 tests failed in shear. Figure 6 shows the comparison between the ultimate load test data and CANDE predictions. In each case the predicted failure mode agrees with the observed failure mode. Good correlation is observed overall; predicted values average 1 percent lower than test results. Note that shear failures show slightly more scatter than flexure failures, as should be expected.

Additional out-of-ground experimental verification of the CANDE reinforced-concrete model has been made with circular pipes in three-edge bearing. Good correlation was observed for load-deformation curves as well as 0.01-in cracking loads and ultimate loads (4).

In-Ground Box Culvert

Test data for buried box culverts are very limited. However, recent research projects by the Kentucky Department of Transportation have provided some instrumented data for buried boxes. In particular, measured soil pressures on a buried box culvert (4x4--10) supported on a dense granular bedding within a bedrock formation are used for this study (15). A schematic idealization of the box-soil system is shown in Figure 7 along with box steel rein-

Figure 3. Box culvert in four-edge bearing.

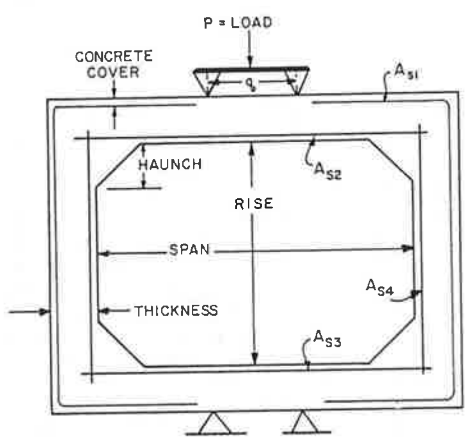


Table 1. Measured properties of test box design.

ASTM Box Size[a]	Concrete Strength f_c' (psi)	Ultimate Steel Strength f_y (ksi)	Load Spacing q (in)	Steel Area[b] (in^2/in)			Load at 0.01-in Crack (kips/ft)	Ultimate Load[c] (kips/ft)
				A_{S1}	A_{S2}	A_{S3}		
8x4–8	4930 5510	84	12	0.025	0.025	0.025	9.3 11.3	17.9 (F) 17.2 (F)
8x4–8	4470 5420	90	12	0.043	0.036	0.036	14.0 12.3	29.7 (F) 22.5 (S)
8x4–8	5280 5850	95	12	0.043	0.043	0.043	13.0 13.5	20.9 (S) 24.5 (S)
6x4–7	7060 7460	94	9	0.015	0.021	0.021	9.5 9.5	16.1 (F) 15.0 (F)
6x4–7	6680 6960	99	9	0.036	0.035	0.027	14.5 10.5	19.4 (S) 25.3 (S)
6x4–7	5960 7190	95	9	0.024	0.034	0.034	15.0 12.5	21.6 (S) 23.4 (S)
4x4–5	6030 6670	96	6	0.011	0.011	0.011	6.7 6.0	9.0 (F) 8.4 (F)
4x4–5	7000 6630	91	6	0.011	0.020	0.020	7.0 8.0	13.2 (F) 13.2 (F)
4x4–5	5710 6430	93	6	0.016	0.027	0.027	7.8 8.5	13.2 (S) 19.3 (F)

[a]Box size given as span (ft) x rise (ft)—wall thickness (in); haunch = wall thickness.
[b]Note A_{S4} steel was not used; spacing of steel wires is 2.0 in; and nominal concrete cover to steel centroids is 1.25 in.
[c](F) = flexure failure, (S) = shear failure.

Figure 4. CANDE model of box culvert in four-edge bearing.

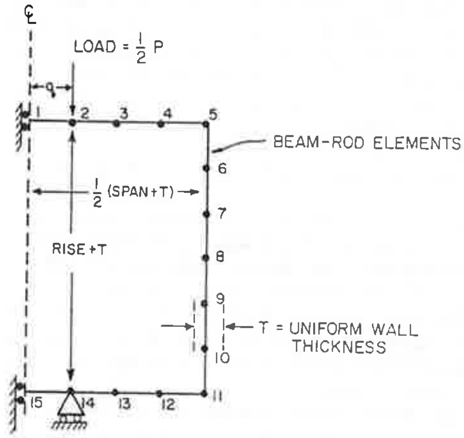


Figure 5. Prediction versus test for load at 0.01-in cracking.

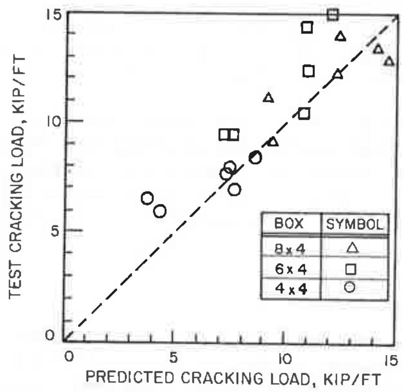
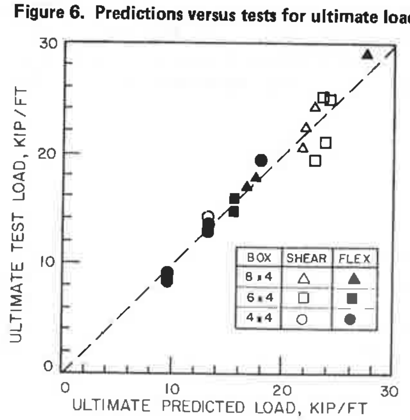


Figure 6. Predictions versus tests for ultimate load.

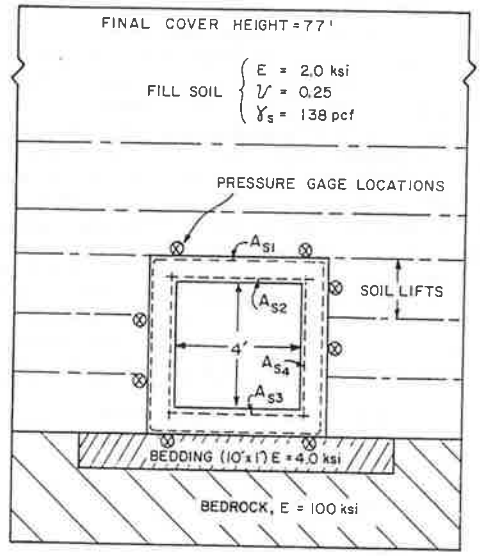


forcement and the location of eight Carlson earth-pressure cells mounted on the box [station 123 + 95 in the report by Russ (15)]. Soil pressure was recorded during the installation process as the fill soil, unified classification MH, was raised to the final cover height of 77 ft.

For the CANDE box-soil model, quadrilateral elements are used to represent the bedrock, bedding, and fill soil, which takes advantage of symmetry about the vertical centerline. Elastic soil properties are assumed as shown in Figure 7. The reinforced-concrete box is modeled similarly to the previous out-of-ground box tests by using the reported material properties. The initial configura-

Figure 7. Schematic view of box-soil system.

REINFORCEMENT AND CONCRETE PROPERTIES	f_c' psi	f_y ksi	STEEL AREAS IN^2/IN A_{s1}	A_{s2}	A_{s3}	A_{s4}
	4500	60	0.037	0.050	0.050	0.017



tion includes bedrock, bedding, and box loaded by its own weight. A total of 20 construction increments are used to simulate the construction process, in which the fill-soil weight density is 138 pcf.

Figure 8 shows the predicted soil-pressure distributions around the box at an intermediate fill height and at the final fill height and corresponding test data points. Good correlation is observed on the top and bottom slabs. Measured pressures on the side walls are not symmetric as assumed in the CANDE model; better agreement is observed for the right wall than for the left wall.

Note that the predicted vertical pressure on the top slab is not uniform as is often assumed in traditional design procedures. This is to be expected due to the stiffness interaction of the fill soil with the slab bending stiffness. As slab cracking develops, a greater portion of the soil load is shifted to the stiffer corners, which are supported by the side walls.

Further experimental verification of CANDE soil-structure models for buried reinforced-concrete pipes is reported elsewhere (1,5). Good correlations are observed for pipe deformations and crack-width predictions during the soil-loading schedule.

EVALUATION OF ASTM C789 BURIED BOX-CULVERT DESIGNS

In the previous sections, the CANDE predictions were shown to correlate well with experimental data for both out-of-ground and in-ground box culverts, including crack widths, ultimate loads, and soil pressures on the box. Thus, a measure of confidence and validity having been established, the CANDE box-soil model is now used to evaluate the ASTM C789 designs that have not been validated with soil-structure analysis for buried conditions prior to this study.

ASTM Box-Culvert Designs

Table 2 shows the 32 standard box dimensions (rise, span, and wall thickness) used in the ASTM C789 design tables. For each box size, there are five or more selections for the amount of steel reinforce-

Figure 8. Prediction versus test data for soil pressure around box culvert.

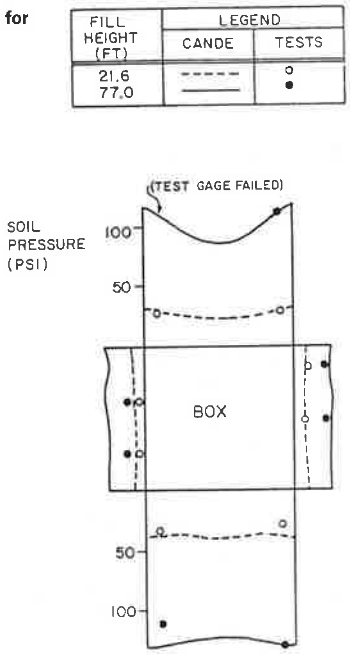


Table 2. Standard box sizes, ASTM C789.

Span (ft)	Rise (ft) 2	3	4	5	6	7	8	9	10	Wall Thickness (in)
3	X	X								4
4	X	X	X[a]							5
5		X	X	X						6
6		X	X	X	X					7
7			X	X	X	X				8
8			X[a]	X	X[a]	X	X[a]			8
9				X	X	X	X	X		9
10				X	X[a]	X	X	X	X	10

[a]Box sizes analyzed with CANDE.

ment, which in turn increases the structural capacity and permits a greater allowable earth-cover height. Shown in Table 3 is a subset of the box-culvert designs in Table 3 of ASTM C789 to be evaluated with CANDE. The sample subset contains five box sizes whose span lengths and rise-span ratios cover the range of standard sizes shown in Table 2. Three amounts of steel reinforcement, listed with each box size, represent low, medium, and high steel percentages from the available choices. Thus, Table 3 contains 15 different reinforced-concrete box-culvert designs whose dimensions and steel percentages represent a reasonable sampling of the larger ASTM design table. For each box-culvert design, ASTM specifies maximum allowable design earth cover, which in this case is the only source of loading (live loads are not considered in Table 3 of ASTM C789).

The ASTM box-culvert designs are based on a computerized design and analysis program (16) that operates with the following steps:

1. Soil pressure distributions are assumed around the culvert in proportion to the design earth-cover height and soil density. Soil pressure on the top and the bottom of the box is assumed uniform, while a linear variation is assumed along the side walls. No shear traction is considered.

2. Moment, shear, and thrust distributions around the culvert are determined by standard matrix methods by using elastic, uncracked reinforced-concrete section properties together with the loading assumptions in step 1.

3. For design, steel areas are determined by an ultimate-strength theory for bending and thrust, where ultimate moments and thrusts are obtained from step 2 multiplied by a load factor of 1.5.

4. Crack width (0.01 in allowable) is checked by using a semiempirical formula that is a function of tensile steel stress at service loads determined in step 2.

5. Ultimate shear stress is checked against the nominal shear stress obtained in step 2 multiplied by a load factor of 1.5.

Table 3. Sample set of box-culvert designs from Table 3 in ASTM C789.

ASTM Box Size	Design Earth Cover (ft)	Steel Amount	Steel Area[a] (in^2/in) A_{S1}	A_{S2}	A_{S3}	A_{S4}
4x3–5	10	Low	0.0100	0.0108	0.0108	0.0100
	14	Medium	0.0100	0.0142	0.0100	0.0100
	18	High	0.0117	0.0183	0.0183	0.0100
8x4–8	6	Low	0.0158	0.0158	0.0158	0.0158
	10	Medium	0.0200	0.0217	0.0255	0.0158
	14	High	0.0283	0.0292	0.0300	0.0158
8x6–8	6	Low	0.0158	0.0158	0.0167	0.0158
	10	Medium	0.0167	0.0242	0.0258	0.0158
	14	High	0.0233	0.0333	0.0350	0.0158
8x8–8	5	Low	0.0158	0.0158	0.0167	0.0158
	8	Medium	0.0158	0.0217	0.0233	0.0158
	12	High	0.0175	0.0308	0.0333	0.0158
10x6–10	6	Low	0.0200	0.0200	0.0200	0.0200
	10	Medium	0.0233	0.0283	0.0300	0.0200
	14	High	0.0325	0.0383	0.0400	0.0200

[a]Steel areas are converted to square inches per inch instead of square feet per inch.

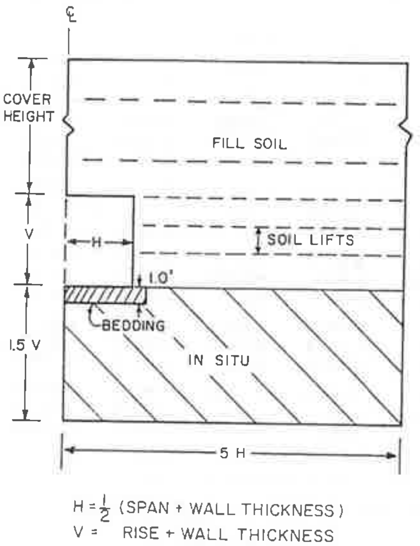
Although the relative simplicity of the above design-and-analysis approach may be attractive, the resulting box designs have not been verified with in-ground experimental tests nor have they been cross-checked with soil-structure interaction analysis prior to this study. Indeed, the assumptions of linear-elastic behavior of concrete, uniform soil-pressure distributions, and the lack of soil-stiffness considerations are but a few of the concerns in assessing the adequacy of the ASTM box designs.

Evaluation Objectives and CANDE Model

For each ASTM box section shown in Table 3, the CANDE box-soil model is used to determine the fill-soil height at which 0.01-in cracking occurs and the fill-soil height at which failure (either shear or flexure) occurs. These fill-soil heights are compared with the corresponding ASTM design earth covers, thereby providing an evaluation of the conservativeness (or unconservativeness) of the box designs.

For the CANDE box-culvert model, the reinforced-concrete parameters listed in Figures 1 and 2 are used, which are consistent with the ASTM specifications. Box dimensions and steel areas are taken directly from Table 3 and haunch dimensions are taken equal to wall thicknesses. Since the ASTM approach does not consider soil stiffness, the CANDE predictions assume two soil conditions--soft and stiff--for the analysis of each box, thereby bracketing the practical range of soil stiffness. Figure 9 shows the box-soil model along with the elastic-modulus values for the soft and stiff soil conditions. The initial configuration consists of in situ soil, bedding, and the box loaded by its own

Figure 9. Box-soil model to evaluate ASTM designs.



SOIL CONDITION *		YOUNG'S MOD. psi	POISSON'S RATIO —
SOFT	FILL	333.	0.33
	BEDDING	666.	0.33
STIFF	FILL	3333.	0.33
	BEDDING	6666.	0.33

* IN SITU = FILL

Figure 10. Evaluation of ASTM box designs of cracking fill cover.

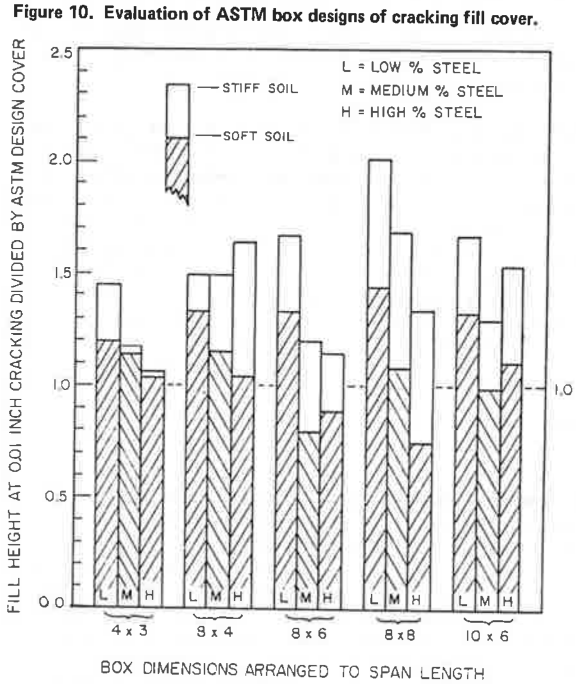
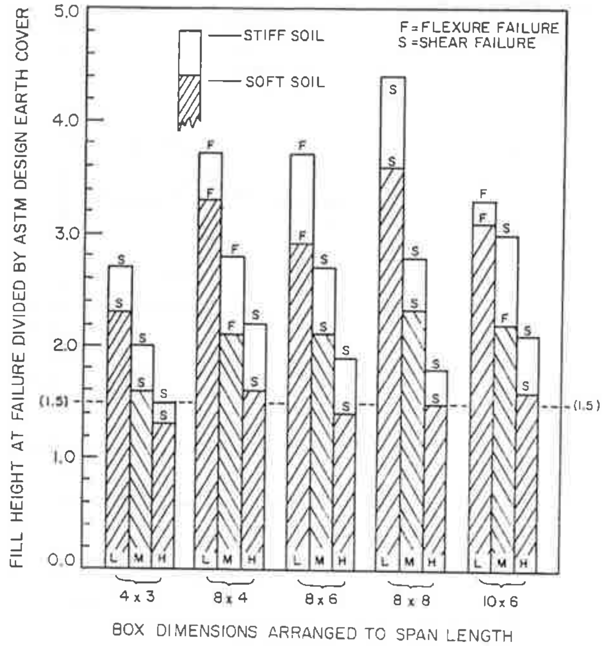


Figure 11. Evaluation of ASTM box design at ultimate fill cover.



weight. Next, nine construction increments of fill soil (weight density = 120 pcf) are sequentially added to the system to raise the fill soil to the ASTM design cover height. Thereafter, additional fill-soil layers are added until a flexural failure mechanism occurs. During this loading sequence, the predicted cover height that causes initial 0.01-in cracking is determined along with the cover height that causes shear failure, providing that shear failure occurs prior to flexure failure (see previous discussion for cracking and failure criteria).

Results of ASTM versus CANDE Cover

Figure 10 shows a bar chart of fill-height ratios formed by dividing the CANDE cover-height prediction for 0.01-in cracking by the corresponding ASTM design earth cover. Here the five boxes, arranged to span size, are grouped into three bar graphs that represent the three levels of steel reinforcement. For each individual bar graph, two fill-height ratios are shown, which result from the soft and stiff soil conditions assumed in the CANDE model.

If the ASTM designs are conservative (safe) with regard to an allowable 0.01-in cracking, these fill-height ratios should be greater than or equal to 1.0. For the stiff soil condition, the ratio ranges from 1.06 to 2.02, which implies conservative designs. However, for the soft soil condition, the ratio ranges from 0.75 to 1.44, which indicates that some designs may not be conservative. As a general conclusion, the ASTM boxes are moderately conservative with respect to 0.01-in cracking at design earth cover providing good quality soil is used.

Figure 11 shows a similar bar chart for fill-height ratios formed by dividing the CANDE cover-height prediction at failure (flexure or shear) by the corresponding ASTM design earth cover. In this case, an ideal design should have a ratio of 1.5 since the ASTM design procedure assumes an ultimate soil loading of 1.5 times the design earth-cover loading. For stiff soils, the ratio varies from 1.5 to 4.4, whereas for soft soils, the ratio varies from 1.3 to 3.6. Thus, in general, the ASTM designs are conservative, perhaps overly conservative when good quality soil is employed.

It is interesting to observe (Figure 11) that for a given box size and soil condition, the ratios are higher for low reinforcement than for high reinforcement. In other words, the ASTM design earth cover specified for a box with low reinforcement is more conservative than the specified earth cover for the identical box with high reinforcement. Another observation indicated in Figure 11 is that shear failure is the predominant failure mode. The likelihood of flexural failure is increased when the span-rise ratio is high, the soil stiffness is low, and/or the steel reinforcement is low.

An observation not made here but reported elsewhere (4) is that the vertical soil-pressure distribution on the top and bottom slabs is not uniform (as in the ASTM loading assumption) but increases monotonically from the box centerline to the corners. Furthermore, the curvature of the pressure distributions becomes more pronounced as the soil-cover height increases due to flexural cracking and weakening of the slabs. Also, the shear traction on the side walls produces a significant downward force that must be equilibrated by an upward pressure on the bottom slab, an effect not taken into account in the ASTM loading assumption.

SUMMARY AND CONCLUSIONS

The CANDE box-culvert model correlates well with experimental data for boxes in four-edge bearing. Predicted loads for 0.01-in cracking averaged 10 percent lower than measured, and predicted ultimate loads averaged 1 percent lower than measured. Measured soil pressures from an in-ground box-culvert installation are in good agreement with CANDE box-soil model predictions at both intermediate and final earth-cover depths.

After the CANDE model has been verified, the ASTM C789 buried box designs are evaluated with CANDE, which results in the following conclusions:

1. Soil stiffness, which is not accounted for in the ASTM design and analysis procedure, has a significant influence on the crack width and structural capacity of buried box culverts. Stiff soils allow as much as 50 percent greater fill heights than do soft soils.
2. Soil shear traction on the side walls, also not accounted for in the ASTM procedure, produces a significant downward force that must be equilibrated by increased pressure on the bottom slab.
3. Specified earth covers for ASTM box designs are safe against exceeding the 0.01-in crack-width limitation if good quality soil and compaction are used.
4. Ultimate earth-cover loading for ASTM box designs is usually significantly greater than 1.5 times the design earth cover, which infers that ASTM designs are conservative. However, designs that require heavily reinforced boxes are less conservative than those for lightly reinforced boxes.
5. Shear failure is the predominant failure mode. The likelihood of flexural failure increases with increased ratio of box span to rise, decrease of soil stiffness, and decrease of steel reinforcement.

Further results and discussion of these findings are given elsewhere (6).

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