

Measurements and Analyses of Deformed Flexible Box Culverts

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Field measurements of 22 in-service flexible box culverts showed that the in-place geometries of these in-service structures may vary from their theoretical geometries. Because the Simplified Design Method (SDM) for box culverts, developed in the early 1980s, was based on small-strain nonlinear finite element analyses (FEM) of box culverts with theoretical "design" geometries, it was necessary to evaluate how structural deformations would affect the induced bending moments that govern box culvert design. Additional FEM studies of deformed and undeformed box culverts show that the current SDM methodology may slightly underestimate the design bending moments for flexible box culverts with installed geometries that differ significantly from their theoretical undeformed geometries. Design bending moments were found to be underestimated by as much as 20 percent for worst-case deformation conditions with shallow crown cover depths. An appropriate minor modification of the SDM methodology is thus proposed.

The Simplified Design Method (SDM) proposed by Duncan et al. for design of flexible metal box culvert structures is based on nonlinear finite element (FEM) analyses augmented by full-scale field load tests (1). The FEM analyses performed in developing the SDM design procedures were based on small-strain analyses of box culverts with theoretical "undeformed" geometries. The actual geometry of a box culvert, however, may deviate from the theoretically "perfect" undeformed geometry as a result of deformations occurring during backfilling and repeated live load applications. In addition, culverts may not be assembled in the field with theoretically ideal initial geometries. This paper presents the results of studies performed to investigate the effects of actual culvert deformations and deformed geometries on the results of FEM analyses and to evaluate the resulting effects on the accuracy and usefulness of the SDM design methodology.

Field measurements were made of the in-place geometries of 22 randomly selected in-service box culvert structures. Three cases where the in-place box culvert geometry varied most significantly from the theoretical geometry were then selected for detailed analysis. These cases of significantly deformed geometries are largely attributed to built-in deformations that occurred during culvert erection and backfilling and to inelastic deformation that resulted from repeated live (vehicle) load application. The in-place deformations raised a question as to the actual factor of safety levels of these worst-case

deformed box culvert structures under their full (HS-20) design loads.

This paper presents the results of nonlinear FEM analyses of these three box culvert structures over a range of conditions to investigate the influence of load-induced deformations and in-place deformed geometries on design moments, investigate the effects of calculated design moments of recent minor improvements in FEM modeling of flexible metal box culvert structures, and expand the analytical data base for the SDM design methodology proposed by Duncan et al. (1). These field measurements and analyses provide a basis for evaluation of the SDM design methodology. As a result of this evaluation, a minor modification in this design methodology is proposed.

FIELD MEASUREMENTS OF IN-PLACE GEOMETRIES

A preliminary survey of the geometries of 17 in-service aluminum box culverts and 5 in-service steel box culverts was performed in the spring of 1988. These 22 culverts had all been in service for periods of from 1 to 9 years. This preliminary survey included measurements of the radius of curvature for both the crown and haunch sections and visual inspection of the culvert interior and the overlying road surface for any signs of distress.

More detailed measurements of geometry were then performed for five box culvert structures that were among the structures most significantly deformed relative to their theoretical undeformed geometries. All five of these box culvert structures had close to the minimum allowable soil cover depth over the crown. Two, with spans of 20.3 and 20.9 ft, had upward crown deflections (peaking) of about 1.5 in., a deformation mode typical of backfill- and compaction-induced deformations for flexible culverts with low cover (2-7). The other three box culverts, with spans of 11.7, 21.8, and 24.4 ft, had downward crown deflections of approximately 2.0, 3.0, and 4.5 in., respectively, and outward haunch deflections of approximately 1.2, 2.3, and 3.0 in., respectively. The probable sources of these observed deflections are discussed later in this paper.

Three box culverts were then selected from among the five significantly deformed structures for further, detailed analyses. These three structures were chosen as having large observed deviations from their theoretical design geometries and as

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providing a fairly broad range of spans, rises, and general shapes.

THE SIMPLIFIED DESIGN METHOD

Duncan et al. (1) proposed the SDM for design of flexible metal box culvert structures. Two basic design formulas were proposed: one for the sum of the maximum moment in each of the crown and haunch sections that develop during backfill placement (M_{TB}) and another for the sum of the increases in maximum moments in the crown and haunch sections that develop during application of the design live load (ΔM_{TL}). These two moment sums are then increased by load factors of 1.5 (for M_{TB}) and 2.0 (for ΔM_{TL}) to obtain the dead load factored moment sum (M_{TB}^*) and the live load factored moment sum (ΔM_{TL}^*) as

$$M_{TB}^* = (1.5)(M_{TB}) \quad (1)$$

$$\Delta M_{TL}^* = (2.0)(\Delta M_{TL}) \quad (2)$$

For structural design, these two factored moment sums are then proportioned between the crown and haunch sections by a coefficient P as

$$M_{CD} = (P)(M_{TB}^*) + (P)(\Delta M_{TL}^*) \quad (3)$$

$$M_{HD} = (1 - P)(M_{TB}^*) + (1 - P)(R_H)(\Delta M_{TL}^*) \quad (4)$$

Since lateral load spreading will occur along the culvert structure during concentrated live loading, the live-load-induced increase in maximum haunch moment is corrected by a reduction factor R_H , the haunch moment reduction factor. R_H varies from 0.65 to 1.0 as a function of crown cover depth and was evaluated by comparison between full-scale load tests and FEM analyses (3). The resulting design moments (M_{CD} and M_{HD}) represent the required design plastic moment capacities for the box culvert crown and haunch regions, respectively.

The recently adopted AASHTO design specifications for flexible metal box culvert structures (8) provide allowable ranges of values for the coefficient P as a function of box culvert span. Within these allowable ranges, the designer can select how the total required plastic moment capacity should be proportioned between the crown and haunch sections.

This paper will not address the issue of a basis for selection of an appropriate coefficient (P) for proportioning the design moments between the crown and haunch sections, but will instead focus on the derivation of the sum of the maximum backfill-induced crown and haunch moments (M_{TB}) and the sum of the maximum live-load-induced crown and haunch moment increases (ΔM_{TL}). For purposes of later discussion, we now define the overall total design moment sum as

$$M_{T,DESIGN}^* = M_{TB}^* + \Delta M_{TL}^* \quad (5)$$

This total, which combines the backfill and live-load-induced factored moment sums, represents the critical core of the SDM design methodology.

FEM ANALYSES OF THREE BOX CULVERT STRUCTURES

The three box culvert structures chosen for analysis were Kaiser Box Culverts 12A (span = 11.7 ft, rise = 5.8 ft), 56B (span = 20.9 ft, rise = 6.1 ft), and 79C (span = 24.4 ft, rise = 8.9 ft). Finite element meshes used for these analyses are shown in Figures 1, 2, and 3. The nodal points at the base boundaries were fixed against translation, and the nodal points at the right and left boundaries were fixed against lateral translation and rotation, but were free to translate vertically. These half-meshes allowed modeling of symmetric loading, after which the live-load-induced increase in maximum crown moment was increased by 10 percent to conservatively reflect the potentially more critical live load location just off center of midspan, as established in earlier studies.

Finite element analyses of the three box culverts were performed using the program SSCOMP (9), a plane strain finite element code for incremental nonlinear analysis of soil-structure interaction. Soil elements were modeled with four node isoparametric elements, and the culvert structures were

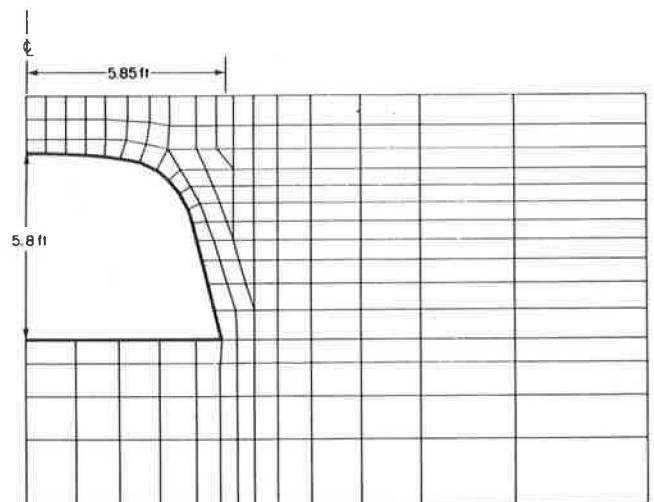


FIGURE 1 Finite element mesh for analysis of Box Culvert 12A.

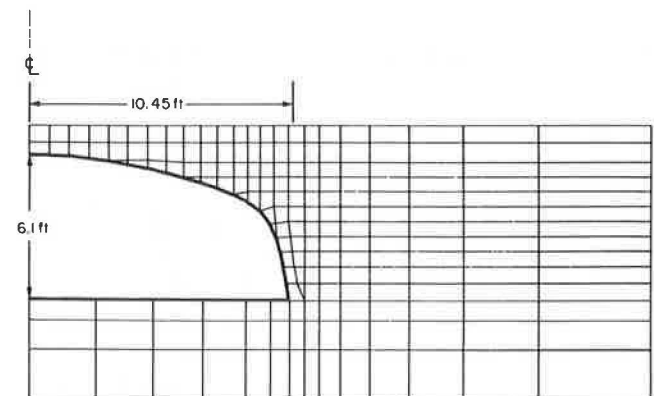


FIGURE 2 Finite element mesh for analysis of Box Culvert 56B.

modeled with piece-wise linear beam elements. Nonlinear stress-strain and volumetric strain soil behavior was modeled using the hyperbolic formulation proposed by Duncan et al. (10) as modified by Seed and Duncan (4). Structural behavior was modeled as linear elastic. The analyses were performed in steps to incrementally model the actual backfill placement process and then the application of design live loading.

The foundation and backfill soils were modeled as a silty clay of low plasticity compacted to 90 percent of the Standard Proctor (ASTM D-698) maximum dry density. This silty clay, which represents the lowest-quality backfill currently permitted for this type of flexible box culvert, has been shown to result in calculation of conservative (upper-bound) design

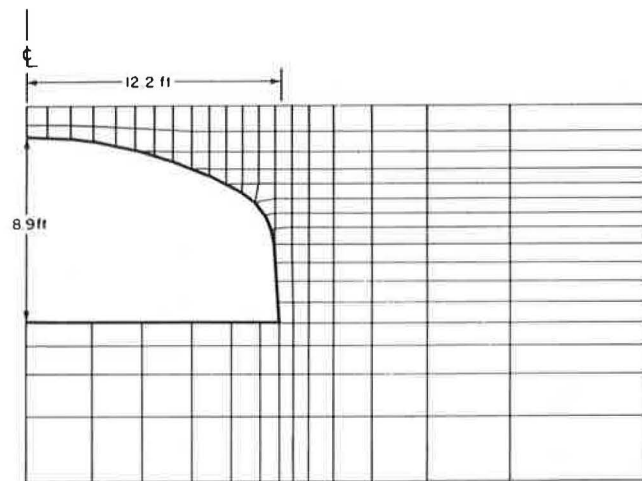


FIGURE 3 Finite element mesh for analysis of Box Culvert 79C.

bending moments in FEM analyses (1, 11). This backfill was modeled using the hyperbolic soil behavior model parameters proposed for a CL-90 backfill by Duncan et al. (10). Analyses were performed modeling the placement of backfill in a series of layers or increments. Foundation soils below the inverts of the culverts were modeled as pre-existing, and the backfill soil elements above this level were placed one layer at a time.

Discrete vehicle loads were represented by equivalent line loads using the equivalent line load estimation procedure proposed by Duncan and Drawsky (11) as modified by Seed and Raines (12). The design load used in all analyses was based on the standard 32-kip HS-20 single-axle design load and was applied after backfill placement was completed.

Structural parameters used to model the various culvert section components are listed in Table 1. Section moduli used to model the corrugated aluminum plate sections are based on large-scale flexural test data. Section moduli for the ribbed sections were modeled as intermediate between the theoretical value for the ribs and plate acting as a composite beam and the theoretical value for the ribs and plate acting independently. This choice of values is also based on large-scale flexural test data and represents the effects of shear slippage at the plate to rib connections (5). These parameter selections have been shown to provide good agreement with measured field deformations for a number of well-documented case studies of flexible metal culvert structures under a variety of backfill and live-loading conditions (3, 4, 6, 7, 12). It should be noted that the flexural behavior of these composite plate/rib sections is nearly linear over stress ranges representing mobilization of less than about 60 to 65 percent of the section's plastic moment capacity (M_p), as demonstrated by Seed and Ou (3). As the SDM load factors provide for a factor of safety with respect to plastic failure in flexure such that actual bending moments are typically less than 65 percent of M_p , this linear

TABLE 1 STRUCTURAL PROPERTIES USED TO MODEL BOX CULVERTS 12A, 56B, AND 79C

Box Culvert	Structural Section	Modulus, E (kips/ft ²)	Area (ft ² /ft)	Moment of Inertia I ($\times 10^{-4}$) (ft ⁴ /ft)
No. 12A	lower haunch	1,468,800	0.0097	0.480
	upper haunch	1,468,800	0.0182	1.428
	crown	1,468,800	0.0254	3.515
No. 56B	lower haunch	1,468,800	0.0122	0.602
	upper haunch	1,468,800	0.0338	4.969
	crown	1,468,800	0.0363	5.346
No. 79C	lower haunch	1,468,800	0.0122	0.602
	upper haunch	1,468,800	0.0338	4.969
	crown	1,468,800	0.0387	5.698

structural modeling provides a good basis for the analyses performed as part of these studies.

EFFECTS OF IMPROVED FEM MODELING

The analysis procedures used in this study employ two minor improvements over the FEM modeling procedures used by Duncan et al. (1): (a) the nonlinear soil behavior model in this study provides improved modeling of the increased stiffness of a soil during unloading and reloading and (b) the section moduli of the ribbed culvert sections are reduced from

the theoretical value for perfect composite action to account for shear slippage between the ribs and the plate. To investigate the effects of these changes, analyses of the theoretical undeformed geometries of Box Culverts 12A, 56B, and 79C were performed using (a) the earlier FEM modeling techniques used by Duncan et al. (1) and (b) the improved modeling techniques described in the previous section.

The theoretical undeformed geometries of each of the three box culvert structures were analysed with three different amounts of final crown cover depth. The results obtained using the FEM techniques used in this study are listed in Table 2a and are plotted on Figures 4 and 5. The results obtained

TABLE 2 CALCULATED MAXIMUM BACKFILL-INDUCED MOMENTS AND LIVE-LOAD-INDUCED MOMENT INCREASES FOR THEORETICAL UNDEFORMED AS WELL AS DEFORMED BOX CULVERT GEOMETRIES

A) Theoretical Undeformed Geometries:

Span (ft)	Cover Depth (ft)	FINITE ELEMENT METHOD					SIMPLIFIED DESIGN METHOD			
		Backfilling		Due to HS-20		Factored ⁽¹⁾ $M_{T,Design}$ (k-ft/ft)	M_{TB} (k-ft/ft)	ΔM_{TL} (k-ft/ft)	Factored ⁽¹⁾ $M_{T,Design}$ (k-ft/ft)	
		M_{CB} (k-ft/ft)	M_{HB} (k-ft/ft)	ΔM_{CL} (k-ft/ft)	ΔM_{HL} (k-ft/ft)					
11.7	1.7	0.6	0.4	6.1	1.8	17.3	1.4	7.3	16.7	
	2.5	0.9	0.5	3.7	1.2	11.9	2.1	5.4	14.0	
	4.0	1.5	0.8	1.9	0.7	8.7	3.4	3.5	12.1	
20.9	1.4	1.2	1.6	9.9	5.9	35.8	3.6	16.2	37.8	
	2.5	2.2	3.0	5.6	3.9	26.8	6.8	10.6	31.4	
	4.0	3.5	4.7	2.5	2.4	22.1	11.1	6.9	30.5	
24.4	1.5	1.6	2.0	9.5	5.1	34.6	4.6	17.0	40.9	
	2.7	2.9	3.6	4.6	3.2	25.4	9.4	10.8	35.7	
	4.0	4.2	5.2	1.9	2.1	22.1	14.5	7.5	36.8	

B) In-Place Deformed Geometries:

11.7	1.7	0.5	0.6	6.3	1.9	18.1	1.4	7.3	16.7
	4.0	1.8	1.0	2.1	0.8	10.0	3.4	3.5	12.1
20.9	1.4	1.5	2.4	11.2	7.1	42.5	3.6	16.2	37.8
	4.0	3.8	6.2	3.4	2.8	27.4	11.1	6.9	30.5
24.4	1.5	1.8	2.7	9.8	5.4	37.2	4.6	17.0	40.9
	4.0	4.6	6.5	2.4	2.3	26.1	14.5	7.5	36.8

C) Extrapolated Geometries from 2 x In-Place Deformations:

11.7	1.7	0.7	0.6	6.9	2.3	20.4	1.4	7.3	16.7
	4.0	2.1	1.2	2.2	0.9	11.2	3.4	3.5	12.1
20.9	1.4	1.8	2.7	12.2	7.8	46.8	3.6	16.2	37.8
	4.0	4.8	7.0	3.8	3.1	31.9	11.1	6.9	30.5
24.4	1.5	3.1	4.9	8.8	6.1	41.8	4.6	17.0	40.9
	4.0	5.1	8.1	3.9	2.7	33.0	14.5	7.5	36.8

D) Predicted Deformed Geometry Under HS-20 Loading:

11.7	1.7	0.6	0.4	6.2	1.8	17.5	1.4	7.3	16.7
20.9	1.4	1.2	1.5	11.5	6.8	40.7	3.6	16.2	37.8
24.4	1.5	1.9	2.3	10.4	5.6	38.3	4.6	17.0	40.9

(1) Load factors: 1.5 for backfill induced moments and 2.0 for live load induced moment increases, so that
 $M_{T,Design} = (1.5)(M_{CB} + M_{HB}) + (2.0)(\Delta M_{CL} + \Delta M_{HL})$ or $M_{T,Design} = (1.5)(M_{TB}) + (2.0)(\Delta M_{TL})$.

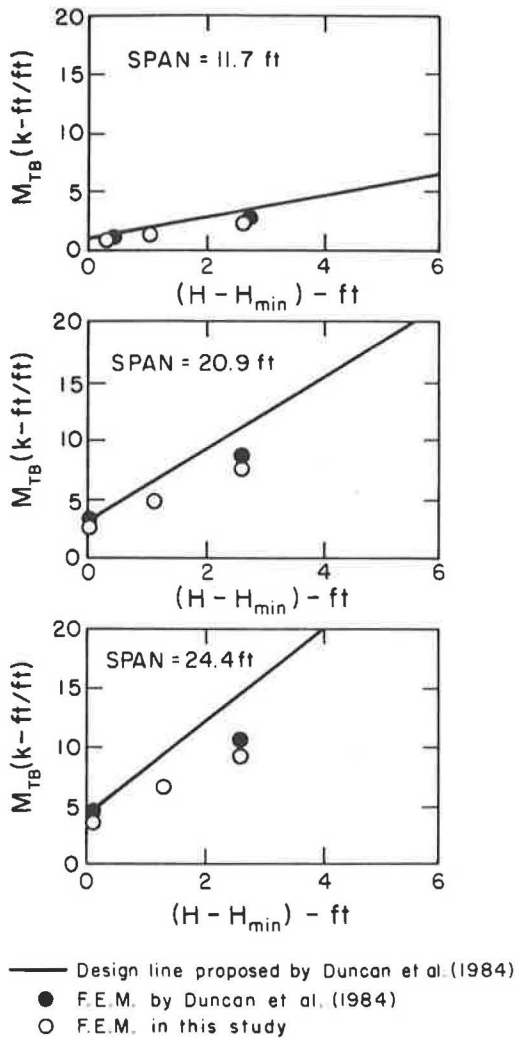


FIGURE 4 FEM-calculated total backfill-induced moments (M_{TB}) as a function of box culvert span and crown cover depth.

using the FEM techniques used by Duncan et al. (1) are plotted on Figures 4 and 5 for comparison. In these figures, H is the final crown cover depth, and H_{min} is the minimum allowable flexible box culvert crown cover depth ($H_{min} = 1.4$ ft).

As shown in these figures, the FEM techniques used in this study gave slightly smaller total moments than did those used by Duncan et al. (1) for both backfill-induced moments (M_{TB}) and live-load-induced moment increases (ΔM_{TL}) for all three culvert spans and all cover depths considered. These slightly smaller moments are due to a slight overall increase in the modeled stiffness of the surrounding soil relative to the stiffness of the culvert structure, which allows the soil to carry a slightly greater share of the load. The coefficient P describing the distribution of total backfill moments (M_{TB}) and live load moment increases (ΔM_{TL}) between the crown and haunch regions was found to be nearly equal for either set of modeling techniques. The differences between the results for either set of FEM modeling techniques are sufficiently small that the analytical data from this study can be combined with the data developed by the analyses performed by Duncan et al. (1) to

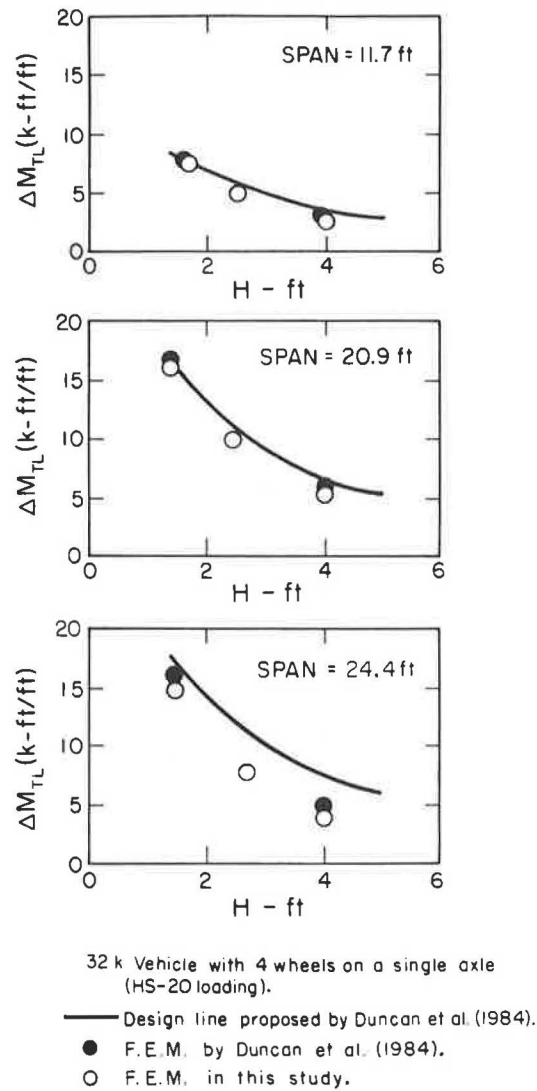


FIGURE 5 FEM-calculated live-load-induced total moment increases (ΔM_{TL}) as a function of box culvert span and crown cover depth.

provide an expanded data base for evaluating the SDM design methodology.

A further comparison of the analytical results from this study with the results of earlier analyses by Duncan et al. (1) is presented in Figure 6 which shows the crown versus haunch moment distribution coefficient P versus span. The three box culvert structures analyzed in this study gave P values that fall largely within the upper range of the data points developed earlier by Duncan et al. (1).

FEM RESULTS FOR DEFORMED BOX CULVERT GEOMETRIES

The bending moments that develop in a box culvert structure under live (vehicular) loading will depend on the deformed geometry at the time of load application. The deformed geometry at that time will include (a) deformations built in during structural erection and backfilling, (b) locked-in elastic defor-

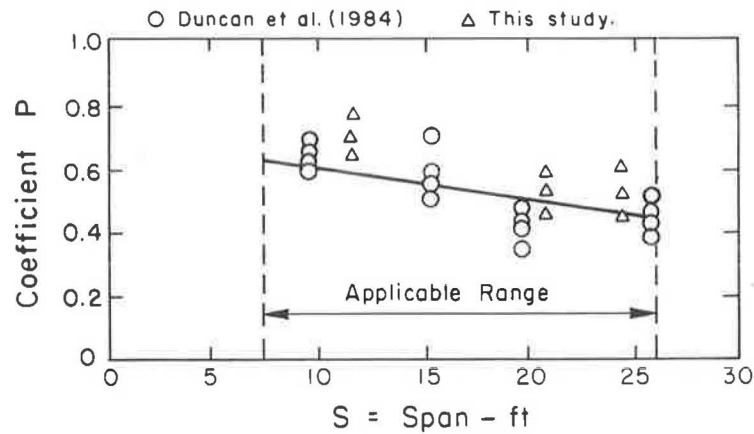


FIGURE 6 Plot of the crown/haunch moment distribution coefficient P versus box culvert span.

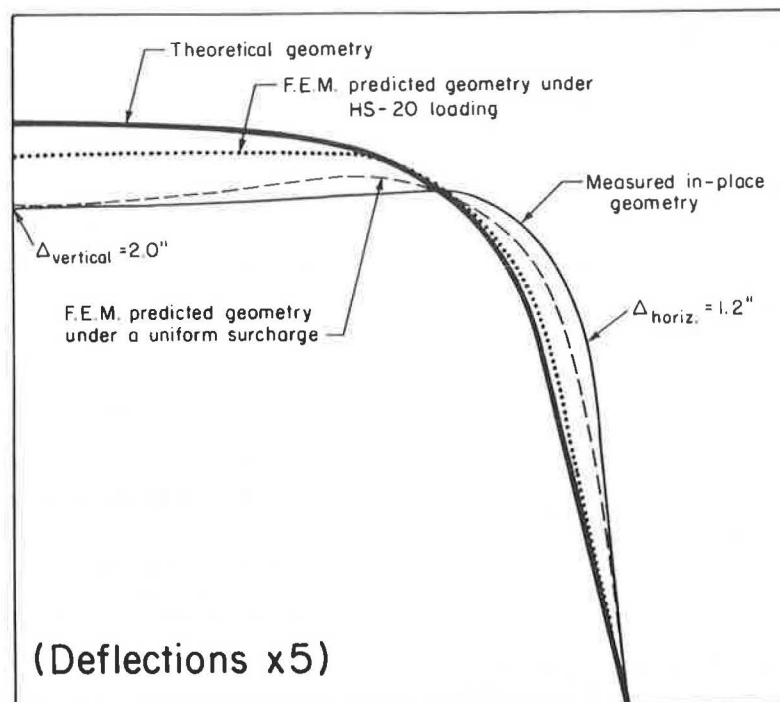


FIGURE 7 Undeformed and deformed geometries of Box Culvert 12A.

mations due to repeated live load applications, and (c) the deformations due to the application of the actual vehicle loading itself. When a vehicular load is removed, both the soil around the culvert and the culvert structure itself are unloaded. Because soil is stiffer in unloading/reloading, and because some inelastic structural deformations may occur (including inelastic shear slippage between the ribs and structural plates), the culvert does not return to its preload geometry but instead retains some residual locked in deformations. After repeated loadings, the live-load-induced deformations become essentially elastic with a magnitude equal to some fraction of that expected for “virgin” (first-time) loading. Thus the in-place deformed geometries come to include some locked-in live-load-induced deformations, and as a result, the culvert will

deform less under subsequent design loading than under virgin loading.

The theoretical undeformed geometries (heavy solid lines) and the actual measured in-place deformed geometries (light solid lines) of Box Culverts 12A, 56B, and 79C, respectively, are shown in Figures 7, 8, and 9. In these figures, all deformations (defined as deviations from the theoretical undeformed geometry) are exaggerated (increased) five times for clarity. The actual in-place deformed geometry of Box Culvert 56B has an upward crown deflection, and this crown peaking results in reduced crown and haunch bending moments under HS-20 live loading. Because a downward crown deflection would be more critical, a hypothetical in-place deformed geometry with a large downward crown deflection for Box

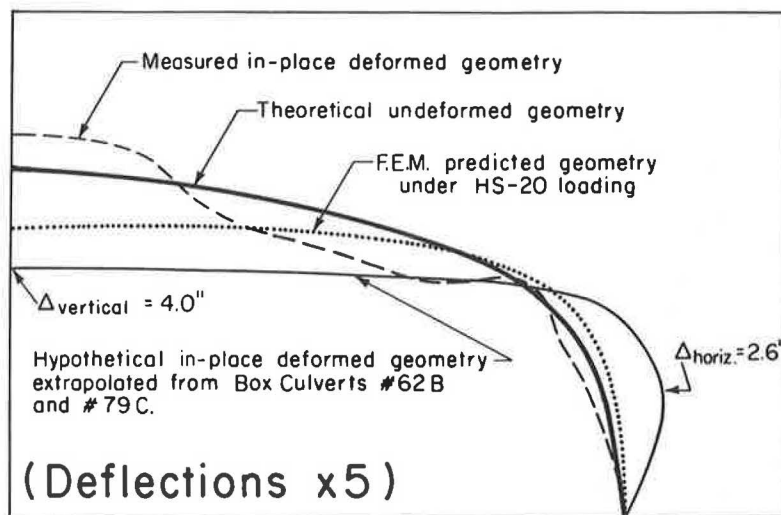


FIGURE 8 Undeformed and deformed geometries of Box Culvert 56B.

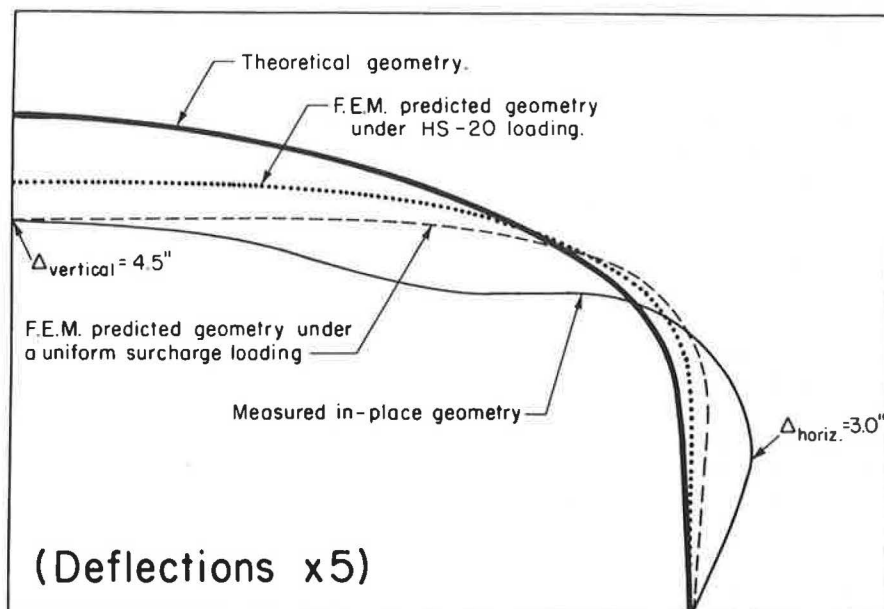


FIGURE 9 Undeformed and deformed geometries of Box Culvert 79C.

Culvert 56B (span of 20.9 ft) was extrapolated from the measured field geometric data for two similar box culverts (spans of 21.8 ft and 24.4 ft) with large downward crown deflections. This hypothetical in-place deformed geometry is also shown in Figure 8.

The FEM results listed in Table 2b are based on the analyses of the actual in-place deformed geometries of Box Culverts 12A and 79C and the hypothetical (downward crown deflection) in-place deformed geometry of Box Culvert 56B. At shallow cover depths, the effects of considering the in-place deformed geometries was to increase the overall calculated bending moments by 3 to 14 percent for the crown section, and by 15 to 28 percent for the haunch section relative to those calculated for the theoretical undeformed geometries as summarized previously in Table 2a. These increases cor-

respond to increases in the calculated backfill-induced moment sum (M_{TB}) of 10 to 39 percent and the calculated live-load-induced moment increase sum (ΔM_{TL}) of 4 to 16 percent, resulting in an increase in the overall required total design moment sum ($M_{T,DESIGN}$) of 5 to 19 percent.

The deformations that resulted in the actual observed in-place deformed geometries of Box Culverts 12A and 79C are attributed largely to built-in deformations (initial erection of the box culvert structure with a nonideal theoretical undeformed geometry) because the magnitudes of the measured lateral haunch movements would be enough to cause passive failure of the surrounding soil, which is an unlikely condition. To demonstrate this, FEM analyses were performed modeling backfilling of Box Culverts 12A and 79C to low final crown cover depths, and then subsequent modeling of the applica-

tion of massive uniform surcharges at the fill surface was performed to generate predicted deformed geometries with the same downward crown deflection as those measured in place. These predicted deformed geometries for massive applied uniform surcharges are also shown (with dashed lines) in Figures 7 and 9. Surface surcharge magnitudes required to generate the observed crown deflections were 2,400 psf for Box 12A and 700 psf for Box 79C. These large surcharges both represent more than two and a half times the allowable (design) surcharges for their respective culverts. Even with these excessively high surcharges, the predicted lateral movements of the upper haunches were much less than the measured field deflections, as shown in Figures 7 and 9.

Since the field measurements obtained for this study may not necessarily represent the worst cases of built-in deformations, deformed geometries were extrapolated to have two times the observed in-place deformations. These hypothetical doubly deformed geometries are expected to conservatively envelope the probable worst-case deflections likely for any acceptably installed flexible metal box culvert structure because the three in-place deformed geometries selected for analysis in these studies represent three structures that were among those found to have the largest deviations from theoretical design geometries among the 22 in-service structures measured.

The FEM results for these doubly deformed geometries are presented in Table 2c. At shallow cover depths, the effect of these doubly deformed geometries was to increase overall calculated bending moments by 5 to 27 percent for the crown section and 36 to 50 percent for the haunch section relative to the moments calculated for the corresponding theoretical undeformed geometries. These increases correspond to increases in the calculated backfill-induced moment sum (M_{TB}) of 30 to 250 percent, in the calculated live-load-induced moment increase sum (ΔM_{TL}) of 2 to 26 percent, resulting in an increase in the total factored moment sum ($M_{T,DESIGN}$) of 18 to 30 percent. It should be noted, however, that for box culvert spans and backfill cover depths where the deformations resulted in the largest increases in bending moments, the SDM design methodology fortuitously tended to provide generously conservative estimates of moment for undeformed geometries. In addition, for those cases in which the backfill-induced moment sum increased most significantly, the contributions of the backfill moments to the overall design moments were relatively small. The net effects of these moment increases on the overall safety of the SDM methodology will be discussed later in this paper.

Predicted deformed geometries for virgin HS-20 loading at midspan of Box Culverts 12A, 56N, and 79C, starting with theoretical undeformed geometries, are also shown (with dotted lines) in Figures 7 through 9. Again it may be observed that the predicted crown deflections are much smaller than the observed deviations of the measured field geometries from the ideal theoretical undeformed geometries. These FEM-predicted deformed geometries under centrally located HS-20 loading were then taken as the initial geometries for another set of analyses, the results of which are listed in Table 2d. This process is equivalent to a first approximation of the adverse effects of large-strain moments versus the moments calculated for undeformed geometries using the small-strain FEM formulation used in all previous studies discussed thus far. For

shallow cover depths, the calculated bending moments were increased by 3 to 15 percent in the crown section and by 3 to 11 percent in the haunch section. These increases in bending moments represent the secondary moments (P -delta effects) for virgin loading of these box culvert structures. However, because the in-place (measured) deformed geometries already include some locked-in live-load-induced deformations, and the deformed box culverts are then somewhat stiffer for subsequent live load application, the effects of these secondary moments for the in-place deformed geometries would be smaller than those predicted for virgin loading of undeformed structures. Accordingly, it was concluded that (a) this first approximation of the P -delta effects was sufficiently accurate, and (b) these secondary P -delta effects do not need to be considered in combination with the deformed geometries considered in these studies, as these deformed geometries were already selected as representing near worst-case conditions.

The total backfill-induced bending moments and live-load-

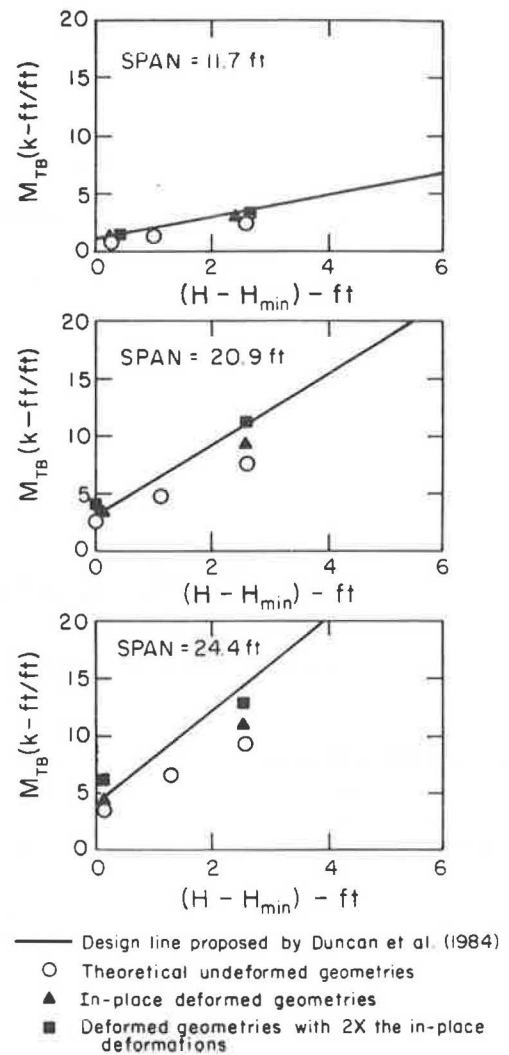


FIGURE 10 FEM-calculated total backfill-induced moments (M_{TB}) as a function of span and cover depth for undeformed and deformed geometries.

induced bending moment increases versus cover depth for the FEM analyses of undeformed and deformed geometries are shown in Figures 10 and 11. For clarity, the plotted data are only for the undeformed and in-place deformed geometries and the extrapolated geometries with two times the in-place deformations. The extrapolated geometries with two times the in-place deformations also provide a conservative upper bound to the results obtained when secondary moments (large-strain or *P*-delta effects) are included in the analyses of the in-place deformed geometries. The solid lines in these figures represent the moments predicted by the SDM design formulas. As shown in these figures, the SDM-predicted total moments (M_{TB} and ΔM_{TL}) tend to be somewhat conservative for large crown cover depths, even for highly-deformed culvert geometries. For shallower cover depths, the SDM-predicted moments are less conservative, and the FEM-calculated moments exceed the SDM moments for highly deformed box culverts with shallow crown cover.

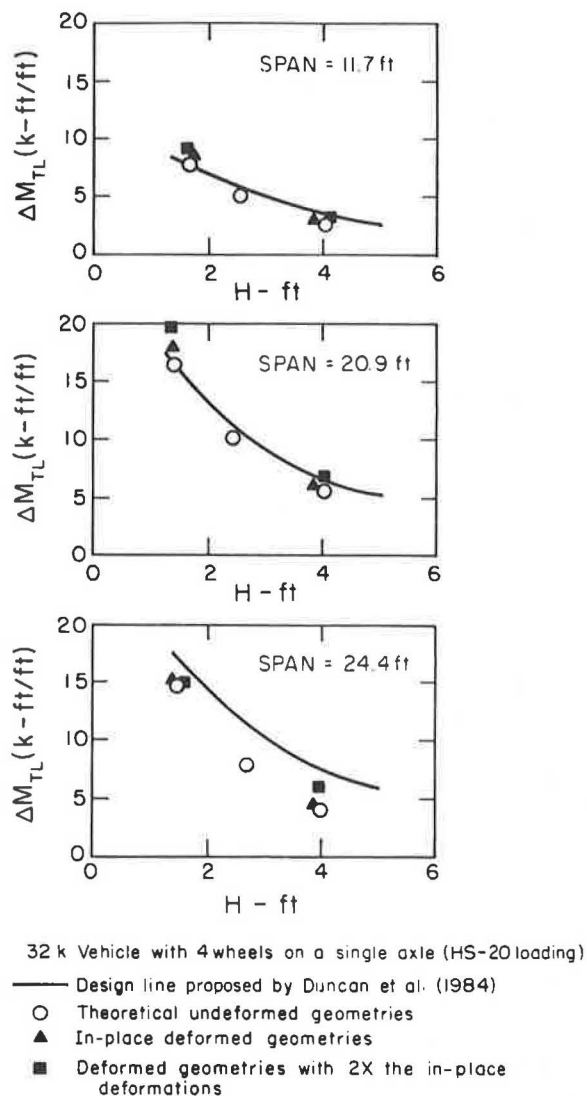


FIGURE 11 FEM-calculated live-load-induced total moment increases (ΔM_{TL}) as a function of span and cover depth for undeformed and deformed geometries.

EVALUATION OF THE SIMPLIFIED DESIGN METHOD

The SDM methodology was evaluated based on the results of the preceding FEM analyses by calculating the ratios of the total design moment sum ($M_{T,DESIGN}^*$) obtained by FEM analyses to the total design moment sum obtained by the SDM design. These ratios

$$\frac{M_{T,DESIGN} (FEM)}{M_{T,DESIGN} (SDM)} = \frac{(M_{TB}^* + \Delta M_{TL}^*)(FEM)}{M_{TB}^* + \Delta M_{TL}^*(SDM)} \quad (6)$$

are presented in Table 3. Because the total design moment sum already incorporates the appropriate load factors, the ratios given in Table 3 provide a direct measure of whether or not the expected factor of safety levels are being obtained. A ratio less than unity implies that the factor of safety level provided by the SDM methodology is greater than required, while a ratio greater than unity implies that the factor of safety level is lower than required.

For example, consider the results for the 20.9-ft-span box culvert with a cover depth of 1.4 ft and the extrapolated geometry with $2 \times$ in-place deformations. The ratio given in Table 3 shows that the SDM methodology underestimates the total design moment sum by 24 percent. Because live-load-induced moments dominate for this structure, the appropriate factor of safety level would ideally be close to 2.0, as dictated by the live load factor of 2.0. An underestimation of total design moment sum by 24 percent would thus be expected to lower the factor of safety (FS) level to close to 1.5. This is shown to be the actual case, based on the FEM analysis results in Table 2, as

$$FS \approx \frac{M_{T,DESIGN} (SDM)}{(M_{TB} + \Delta M_{TL})(FEM)} = 1.54 \quad (7)$$

which provides an estimate of the overall factor of safety level provided by the SDM methodology for this box culvert. This example demonstrates how the ratios given in Table 3 (using Equation 6) clearly identify situations where a lower than appropriate factor of safety level may occur while the overall factor of safety level may be misleading.

The ratios given in Table 3 are also plotted in Figure 12. It is clear that the SDM methodology slightly underestimates total design moments at the minimum cover depth of 1.4 ft, although being adequately conservative for cover depths of 4 ft or more. It also appears that this underestimation at shallow cover depths is largely independent of the spans of the box culverts.

Based on the expanded data base of FEM analyses, it appears that a more reliably conservative correlation between the SDM and FEM estimates of live-load-factored moment sum (ΔM_{TL}^*) and dead-load-factored moment sum (M_{TB}^*) can be obtained by the application of a modest correction factor to increase design moments for situations of shallow crown cover. A new correction coefficient for shallow covers, C_H , is thus introduced. The dead-load-factored moment sum (M_{TB}^*) and the live-load-factored moment sum (ΔM_{TL}^*) would then be calculated as

$$M_{TB}^* = (1.5)(M_{TB})(C_H) \quad (8)$$

TABLE 3 COMPARISON OF TOTAL DESIGN MOMENT SUMS OBTAINED BY THE SDM METHODOLOGY AND BY FEM ANALYSES

Span (ft)	Cover Depth (ft)	$\frac{M_{T,Design} (FEM)}{M_{T,Design} (SDM)}$			
		Theoretical Undeformed Geometries	In-Place Deformed Geometries	Extrapolated Geometries from 2x In-Place Deformations	Predicted Deformed Geometry under HS-20 Loading
11.7	1.7	1.04	1.08	1.22	1.05
	2.5	0.85	--	--	--
	4.0	0.72	0.83	0.93	--
20.9	1.4	0.95	1.12	1.24	1.08
	2.5	0.85	--	--	--
	4.0	0.72	0.90	1.05	--
24.4	1.5	0.85	0.91	1.02	0.94
	2.7	0.71	--	--	--
	4.0	0.60	0.71	0.90	--

$$\Delta M_{TL}^* = (2.0)(\Delta M_{TL})(C_H) \quad (9)$$

replacing Equations 1 and 2. The proposed value of C_H would decrease linearly from 1.15 (a 15-percent increase) at the minimum cover depth of 1.4 ft, to 1.0 at a cover depth of 3.5 ft, as shown in Figure 13. The proposed line for C_H presented in Figure 13 is also overlaid for reference as a dashed line in Figure 12. As shown in these figures, the proposed correction coefficient C_H ensures that the resulting modified SDM methodology provides an increased factor of safety for cases of shallow crown cover.

SUMMARY AND RECOMMENDATIONS

Nonlinear finite element analyses of flexible metal box culvert structures were performed after field measurements identified cases where in-service shapes differed from their ideal design shapes. This raised a question as to the actual factor of safety under full HS-20 design loads. Analyses were performed for undeformed and deformed box culverts with a range of spans and crown cover depths to investigate the influence of a number of factors on required design moments. These factors included (a) load-induced deformations and in-place deformed geometries and (b) recent improvements in FEM modeling of flexible metal box culverts. These additional finite element analyses were then used to evaluate the Simplified Design Method (SDM) developed by Duncan et al. (1).

The current SDM methodology was found to slightly under-

estimate the total design moment sum for likely worst-case deformed geometries with shallow cover depths. Since the components of the total design moment sum form the basis for structural design, the SDM provided lower than desired factor of safety levels in these situations. Accordingly, a minor modification of the SDM is proposed to increase the required design moment capacities by an amount varying linearly from 15 percent at the minimum cover depth of 1.4 ft to 0 percent at a cover depth of 3.5 ft. This proposed modification involves the introduction of a new correction coefficient C_H . The result of this relatively modest modification of the SDM is a slight increase in required design moment capacities for conditions of shallow cover. The new required design moment capacities provide a somewhat more conservative design for likely worst-case deformed box culvert geometries. It should be observed that while the structures evaluated had slightly lower factors of safety than originally predicted, these and other similarly deformed box culverts should continue to perform successfully.

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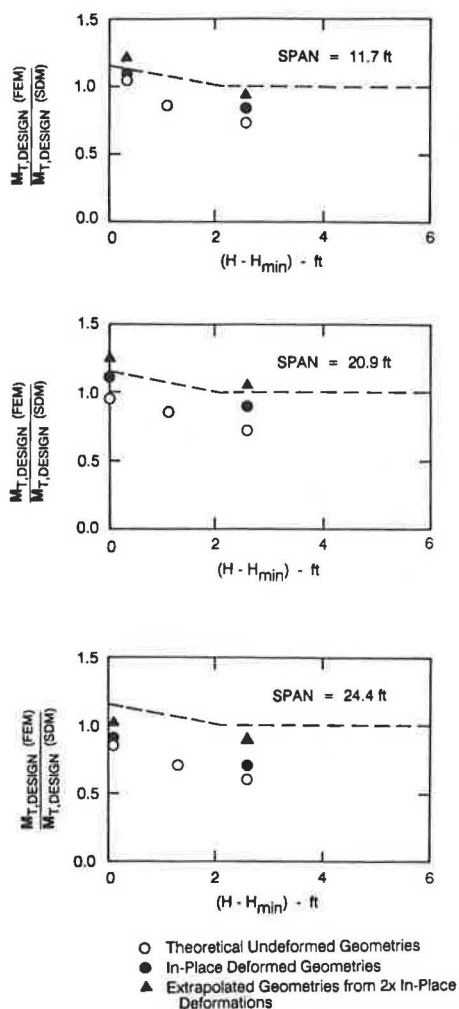


FIGURE 12 Comparison between total design moment sums obtained by the SDM methodology and by FEM analyses.

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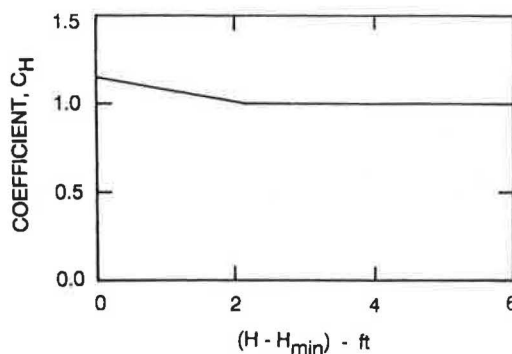


FIGURE 13 Proposed correction coefficient, C_H .

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