Bridge Replacement Cost Analysis

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As part of a study to develop a comprehensive bridge management system for the Indiana Department of Highways, statistical analyses were performed on bridge replacement costs. It was found that unit superstructure cost can be estimated reasonably well in terms of dollars per square foot of deck area. However, the current practice of expressing unit substructure cost in terms of dollars per square foot of deck area only by superstructure type may not adequately account for the difference in substructure costs caused by different substructure types such as solid-stem piers and pile-bent piers. Average unit substructure costs should be computed separately by substructure type as well as by superstructure type. Estimation of approach construction costs has been considered difficult and impractical because of various factors affecting such costs. However, an analysis of variance (ANOVA) can be used. Although approach costs vary significantly from site to site, it was possible to develop cost prediction models that would provide reasonably reliable preliminary cost estimates for bridge engineers and inspectors.

As part of a study to develop a comprehensive bridge management system for the Indiana Department of Highways (IDOH), statistical analyses were performed on bridge replacement costs. It was found that unit superstructure cost can be estimated reasonably well in terms of dollars per square foot of deck area by superstructure type. However, the current practice of computing unit substructure cost per square foot of deck area only by superstructure type may not be adequate to fully account for the difference in costs caused by different types of substructures, such as solid-stem piers and pile-bent piers. It was also found that approach construction costs can be estimated fairly accurately. An ANOVA approach was used to find mean costs and their 95 percent confidence intervals for a group of approach-length and approach-earthwork combinations.

Detailed descriptions and results of statistical analyses performed on unit structure costs and approach construction costs are discussed; these analyses were part of the replacement cost analysis.

DATA BASE

Only state-owned bridges were used for this analysis. Bridges replaced between 1980 and 1985 were selected for statistical analyses. Two hundred seventy-nine state-owned bridges were replaced during this period in Indiana. Currently, IDOH groups newly designed bridges into five types: reinforced-concrete box beam, reinforced-concrete slab, concrete I-beam, steel beam, and steel girder. Because only a few box beam bridges have been designed, they were grouped with reinforced-concrete slab bridges. The Bridge Design Section of IDOH keeps all the records needed for this analysis.

Cost data used in this analysis were actual bridge contract costs awarded to contractors and unit costs computed by IDOH from these contract costs. Replacement costs in different years were adjusted to the 1985 price using the FHWA construction price invoices (*1*).

Data obtained were examined for their suitability to subsequent analyses. It was found that some bridge construction contracts included two bridges together. Where it was difficult to separate costs for each bridge, such data were excluded from the input data set. Bridges with unnecessarily high or low costs relative to the normal range of construction costs were also excluded. Furthermore, bridges that had no approach-road length were considered outside the population of interest for this study.

RESULTS OF PRELIMINARY ANALYSES

After preliminary analyses, it was found that predictions would be practical and reliable if some cost items were grouped. Four cost components were defined: superstructure, substructure, approach, and "other." The "other" cost included other structure, mobilization and demobilization, traffic control, demolition, and miscellaneous costs, which included construction engineering, training, and field office costs.

Table 1 shows percentage splits of these four cost components by bridge and superstructure type. The superstructure cost component accounted for about one-third of the total bridge construction cost for concrete and steel beam bridges, whereas it was about 45 percent for steel girder bridges. The second largest cost component was the approach construction

TABLE 1 AVERAGE PERCENTAGE OF CONTRIBUTION TO TOTAL BRIDGE COST BY FOUR COST COMPONENTS

Cost Component	Bridge Type				
	A	B	C	D	All
I	31.11	31.10	33.42	45.63	32.63
II	11.82	16.69	15.64	15.50	13.53
III	39.45	36.84	36.94	26.35	37.52
IV	17.63	15.38	14.01	12.51	16.33

NOTE: Cost components: I = superstructure; II = substructure; III = approach; IV = other. Bridge types: A = box beam and RC slab (112 samples); B = concrete I-beam (36 samples); C = steel beam (22 samples); D = steel girder (16 samples).

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cost; it accounted for about one-third of the total construction cost. The remaining one-third was split between the substructure cost and other cost.

STUDY APPROACH

ANOVA was performed to evaluate the degree of the impact of classification factors on unit costs. Three factors were used for analyses: superstructure type, substructure type, and highway type. Table 2 shows the levels of these three fixed factors originally considered in the analysis. Superstructure type is the main structure type, as specified by the FHWA guide (*2*). Four superstructure types were considered: reinforced-concrete slab and box beam, concrete I-beam, steel beam, and steel girder.

TABLE 2 CLASSIFICATION FACTORS CONSIDERED FOR UNIT STRUCTURE REPLACEMENT COST ANALYSIS

Factor	Level
Superstructure type	Box beam and RC slab
	Concrete I-beam
	Steel beam
	Steel girder
Substructure type	Solid-stem piers
	Pile-type piers
	Abutment only or arch type[a]
Highway type	Interstate[a]
	Primary
	Secondary
	Urban
	Off-system

[a]Only a few samples were available for analysis.

For substructure type, three groups were used. Bridges with hammerhead piers and solid-stem piers were classified as belonging to the same group because the only difference between these two types was the cantilever portion of the hammerhead piers. Bridges with pile-type piers require far less material than those with solid-stem piers. Therefore, these bridges were grouped separately. The last group includes bridges that do not have piers: bridges supported solely by abutments and arch bridges.

Highway type was considered to determine whether functional highway classification, such as Interstate or primary, would affect the construction cost of superstructures. FHWA requires the state to provide separate unit costs for different highway types, such as those listed in Table 2.

RESULTS OF ANALYSIS OF VARIANCE

Unit Structure Costs

Unit structure costs were divided into three groups: superstructure, substructure, and total structure costs. FHWA requires the state to report these unit costs by superstructure and highway types. One major objective was to examine whether these factors would substantially affect the estimation of unit structure costs.

Unit Superstructure Cost

Because the model used for the ANOVA on unit superstructure cost had unequal cell frequencies, the MANOVA procedure of the SPSS package was used (*3*). A model of four superstructure types and five highway types was originally designed. However, it was found that only a few bridges were replaced on Interstate highways and urban federal-aid highways. Therefore, these two highway types were excluded from the analysis. Among the remaining three highway types, however, bridges on off-system highways caused a significant heterogeneity of variance in this model. As shown in Figure 1, standard deviations of unit costs of bridges on primary and secondary highways appeared to be fairly constant at different levels of mean values. However, the standard deviation of unit costs of bridges on the off-system state highways showed substantial differences at various levels of mean values, causing the heterogeneity of variances for this three-level model. The existence of heterogeneous variances among the cells violates one of the basic assumptions of the ANOVA.

It was not possible to reduce this large variance by commonly used transformations of raw data values. Because of the persistent disturbance of homogeneity of variances created by unit costs of bridges on the off-system state highways and the relatively few bridges replaced on this highway system, it was decided that off-system bridges be excluded from the analysis and the number of levels for highway types be reduced to two, primary and secondary highways. Strictly speaking, therefore, the inference drawn from this analysis can be made only for these two highway types. Unit structure costs of bridges on Interstate, urban, federal-aid, and off-system highways need to be analyzed after an adequate number of bridges have been replaced on these systems.

Consequently, the reduced ANOVA model performed was

$$C_{ijk} = \mu + H_i + S_j + HS_{ij} + \varepsilon_{(ij)k}$$

where

C_{ijk} = unit superstructure cost,
μ = the grand mean,
H_i = highway type,
S_j = bridge type,
HS_{ij} = interaction of highway type by superstructure type, and
$\varepsilon_{(ij)k}$ = error term.

The k subscript on the error term was included to emphasize replication of unit cost samples. Both classification factors were treated as fixed factors. With the reduced model, the Cochran C-test statistic was 0.227 and the homogeneity of variance was accepted at $\alpha = 0.03$. Anderson and McLean (*4*) state that if the homogeneity test is accepted at $\alpha = 0.01$, there is no need to transform the data. Therefore, no data transformation was performed, and the ANOVA was conducted on the raw data.

Because of the sequential sum-of-squares method used by the MANOVA procedure (*3*), the result of the ANOVA is affected by the order in which the two main factors, superstructure type and highway type, are introduced into the model. The sums of squares for each factor effect are adjusted for all effects previously entered into the model (*3*). Therefore, two runs were made, one with the superstructure type as the first entry and the other with the highway type as the first entry. Table 3 is one of these ANOVA tables resulting from the reduced model. It was found that in both cases effects of highway type and the interaction of two factors on the mean

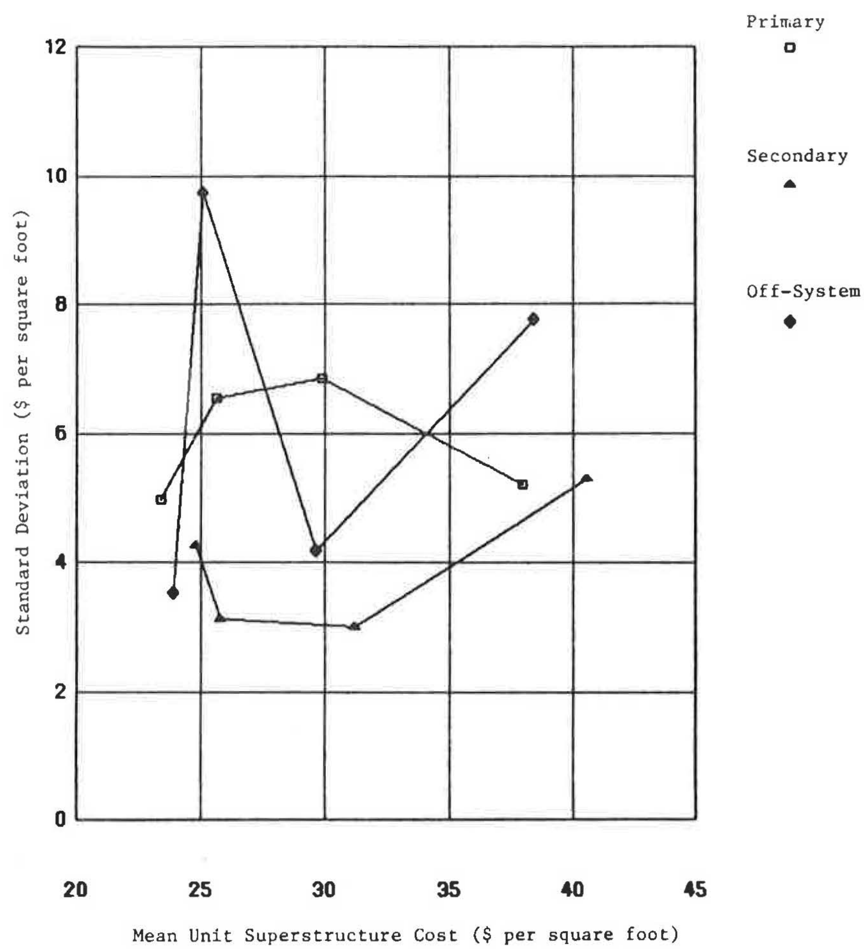

FIGURE 1 Mean versus standard deviation of unit superstructure cost.

TABLE 3 ANOVA FOR HIGHWAY TYPE BY SUPERSTRUCTURE TYPE ON UNIT SUPERSTRUCTURE COSTS

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	*F*-Value	Significance of *F*
Within cells (error term)	4,554.65	190	23.97		
Constant	141,876.18	1	141,876.18	5,918.45	0[a]
HWYTP	11.81	1	11.81	0.49	0.484[b]
SUPTP	2,716.48	3	905.49	37.77	0[a]
HWYTP by SUPTP	25.49	3	8.5	0.35	0.786[b]

NOTE: Cochran *C*-statistic = 0.227; probability = 0.030 (approximately); SUPTP = superstructure type (main effect); HWYTP = highway system type (main effect); SUPTP by HWYTP = interaction effects of highway type by superstructure type.
[a]Significant at the 0.05 level.
[b]Not significant at the 0.05 level.

unit costs were not significant at a 5 percent level. Therefore, with available data, it was concluded that as far as unit superstructure cost is concerned, the only major factor affecting mean cost values was superstructure type. Table 4 shows the mean unit costs, standard errors of the mean (SE), and the upper limit (UL) and lower limit (LL) of the 95 percent confidence intervals. This table shows that only a small difference exists between the mean unit costs and the 95 percent confidence intervals of the two highway types.

Unit Substructure Cost

Unit substructure costs are currently expressed in dollars per square foot of deck area and classified by highway and superstructure type. Considering the diverse factors affecting substructure constructions, such as the location of the foundation and the substructure type, it may be too simplistic to classify unit costs only by superstructure type for accurately estimating actual substructure cost. An ANOVA was therefore performed on unit substructure costs using the superstructure type and the substructure type as the main effects to examine whether the substructure type should be considered to compute unit substructure costs. The substructure type was selected because it was the next logical choice for factoring unit substructure costs. Effects of highway class were assumed to be small judging from the results of analyses on unit superstructure costs.

TABLE 4 TWO-WAY ANOVA DESIGN FOR UNIT SUPERSTRUCTURE COST ANALYSIS

	Superstructure Type			
Highway Type	Box Beam and RC Slab	Concrete I-Beam	Steel Beam	Steel Girder
Primary				
N	47	23	14	10
Mean	25.62	23.40	29.90	37.94
SE	0.71	1.02	1.31	1.55
LL	24.23	21.40	27.33	34.90
UL	27.01	25.40	32.47	40.98
Secondary				
N	72	21	7	4
Mean	25.81	24.81	31.19	40.58
SE	0.58	1.07	1.85	2.45
LL	24.67	22.71	27.56	35.78
UL	26.95	26.91	34.82	45.38

NOTE: *N* = number of samples; mean = mean unit superstructure cost ($/ft^2 of deck area); SE = standard error of the mean; LL = lower limit of 95 percent confidence interval; UL = upper limit of 95 percent confidence interval.

Table 5 shows the model considered in this analysis along with mean unit costs, standard errors of the mean, and 95 percent confidence intervals. Two substructure types were used—solid-stem piers and pile-type piers. The third type, bridges with only abutments or arch support, was excluded from this analysis because only a few samples were found in this group.

Table 6 is the ANOVA table for the model considered. The Cochran *C*-test statistic was 0.225 and the homogeneity test was accepted at $\alpha = 0.05$. Therefore, there was no need for data transformation. It was found that the interaction of the two main effects was significant at the 5 percent level as well as the main effects, as shown in Table 6. The unit substructure costs for the different superstructure and substructure combinations indicated that superstructure type had less effect on unit substructure cost for the bridges with solid-stem type piers than for the bridges with pile-type piers. This differential influence of superstructure type, which depends on the type of substructure, implies that the superstructure and substructure factors interact in their effect on unit substructure costs. Thus, one should not ordinarily discuss the effects of each factor separately in terms of the factor-level means.

Generally, pile-type substructures are expected to cost less. This trend was found for superstructures made of reinforced concrete. However, for steel-beam bridges, pile-type substructures became more expensive than solid-stem piers. The result therefore did not substantiate the expected trend. The small number of samples for this type might have affected the result. However, from these analyses, it can be concluded that the substructure type does affect the unit substructure cost in terms of dollars per square foot of deck area and that adding the substructure grouping should help improve the accuracy of estimated substructure costs.

TABLE 5 TWO-WAY ANOVA DESIGN FOR UNIT SUBSTRUCTURE COST ANALYSIS

	Superstructure Type			
Substructure Type	Box Beam and RC Slab	Concrete I-Beam	Steel Beam	Steel Girder
Solid-stem piers				
N	27	30	13	13
Mean	13.60	14.19	14.29	12.88
SE	0.98	0.93	1.41	1.41
LL	11.68	12.37	11.53	10.12
UL	15.52	16.01	17.05	15.64
Pile-type piers				
N	91	7	7	
Mean	8.30	11.34	19.07	No sample available
SE	0.53	1.92	1.92	
LL	7.26	7.58	15.31	
UL	9.34	15.10	22.83	

NOTE: *N* = number of samples; mean = mean unit substructure cost ($/ft^2 of deck area); SE = standard error of the mean; LL = lower limit of 95 percent confidence interval; UL = upper limit of 95 percent confidence interval.

Unit Total Structure Cost

Unit total structure cost is simply the sum of unit superstructure cost and unit substructure cost. In the previous section, the effect of substructure type on unit substructure costs was discussed. Whether this effect still remains in unit total structure costs was tested because the effect of substructure type might be reduced when added to unit superstructure costs. The same model used for the unit substructure cost analysis was used by replacing unit substructure costs with unit total structure costs.

Table 7 gives the ANOVA results. The homogeneity test was accepted at $\alpha = 0.001$. Anderson and McLean suggested that if the test is accepted between $\alpha = 0.01$ and 0.001, transformation is not needed unless there is a practical reason to transform (*4*). A histogram of raw data was plotted and it was found that total unit structure cost data were normally distributed. Raw data were transformed by common logarithm to see whether the scattering of data points was normally distributed. Two histograms showed basically the same shape and it was concluded that transformation of raw data was not required.

TABLE 6 ANOVA FOR SUPERSTRUCTURE TYPE BY SUBSTRUCTURE TYPE ON UNIT SUBSTRUCTURE COSTS

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Significance of F
Within cells (error term)	4,669.91	181	25.80		
Constant	23,770.58	1	23,770.58	921.32	0
SUPTP	1,050.88	3	350.29	13.58	0[a]
SUBTP	354.38	1	354.38	13.74	0.0003[a]
SUPTP by SUBTP	381.55	2	190.77	7.39	0.001[a]

NOTE: Cochran C-statistic = 0.225; probability = 0.124 (approximately); SUPTP = superstructure type (main effect); SUBTP = substructure type (main effect); SUPTP by SUBTP = interaction effects of superstructure type by substructure type.

[a]Significant at the 0.05 level.

TABLE 7 ANOVA FOR SUPERSTRUCTURE TYPE BY SUBSTRUCTURE TYPE ON UNIT TOTAL STRUCTURE COSTS

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Significance of F
Within cells (error term)	8,888.17	181	49.11		
Constant	272,007.30	1	272,007.30	5,539.20	0
SUPTP	4,577.20	3	1,525.73	31.07	0[a]
SUBTP	312.00	1	312.00	6.35	0.013[a]
SUPTP by SUBTP	218.08	2	109.04	2.22	0.112[b]

NOTE: Cochran C-statistic = 0.296; probability = 0.001 (approximately); SUPTP = superstructure type (main effect); SUBTP = substructure type (main effect); SUPTP by SUBTP = interaction effects of superstructure type by substructure type.

[a]Significant at the 0.05 level.
[b]Not significant at the 0.05 level.

The interaction was dramatically reduced and it became not significant at a 5 percent level (α = 0.112 with raw data). However, two main effects were still significant at a 5 percent level. From this analysis it can be said that the substructure type does affect unit total structure costs as well as does the superstructure type. Therefore, it will be better to compute total superstructure costs separately for the two substructure groups to better estimate replacement costs.

Approach Construction Cost

Approach construction costs for new bridges are difficult to estimate because of many factors affecting the construction of approach roads. Because of this diversity of site-specific factors, approach costs are often estimated as a lump-sum value relative to structure costs. However, at the state level of bridge management, prediction of approach costs is an important element because it would account for a substantial portion of the total construction cost once approach roads are needed. Approach length and amount of earthwork were selected as two classification factors. Approach length was defined as the length of the project after the bridge structure length has been subtracted. The earthwork was the sum of common excavation, borrow, and excavation for subgrade treatment.

Histograms of approach length and earthwork were plotted and samples were classified into three groups, each consisting of approximately one-third of the entire data set. Approach length was divided into three groups—short, medium, and long—whereas earthwork was divided into three levels—short, medium, and large. Ranges for these groups are as follows: (a) Approach length (L): short, 0 ft < $L \leq$ 500 ft; medium, 500 ft < $L \leq$ 1,000 ft; long, 1,000 ft < $L \leq$ 5,280 ft. (b) Approach earthwork (E): short, 0 yd^3 < $E \leq$ 2,000 yd^3 < $E \leq$ 2,000 yd^3; medium, 2,000 yd^3 < $E \leq$ 8,000 yd^3; large, 8,000 yd^3 < $E \leq$ 50,000 yd^3.

Table 8 shows the ANOVA model used for this analysis. Although each cell did not have an equal sample size, each row and column had approximately one-third of the entire sample.

The homogeneity test was rejected at α = 0.001 for raw data and the transformation was made by using common logarithm (log 10). With the transformed data, the Cochran C-statistic was 0.208 and the homogeneity of variance was

TABLE 8 TWO-WAY ANOVA DESIGN FOR APPROACH COST ANALYSIS

Approach Length	Amount of Earthwork: Small	Medium	Large
Short			
N	47	15	3
Mean	80.1	121.1	179.8
LL	70.1	95.5	105.5
UL	91.6	153.7	306.2
Medium			
N	13	40	21
Mean	121.0	158.4	268.9
LL	93.7	136.9	219.9
UL	156.2	183.3	328.9
Long			
N	–[a]	7	46
Mean	–	257.8	330.7
LL	–	181.9	288.7
UL	–	365.4	378.8

NOTE: N = number of samples; mean = mean approach construction cost (in \$1,000); LL = lower limit of 95 percent confidence interval; UL = upper limit of 95 percent confidence interval.

[a]No sample available.

TABLE 9 ANOVA FOR APPROACH LENGTH AND AMOUNT OF EARTHWORK ON APPROACH CONSTRUCTION COSTS

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Significance of F
Within cells (error term)	7.698	184	0.0418		
Constant	946.677	1	946.677	22,626.59	0
LENGTH	8.705	2	4.353	104.03	0[a]
EARTH	1.773	2	0.887	21.19	0[a]
LENGTH by EARTH	0.0076	3	0.025	0.60	0.614[b]

NOTE: Cochran C-statistic = 0.208; probability = 0.110 (approximately); LENGTH = approach length (main effect); EARTH = amount of earthwork (main effect); LENGTH by EARTH = interaction effects of approach length by the amount of earthwork.

[a]Significant at the 0.05 level.
[b]Not significant at the 0.05 level.

accepted at $\alpha = 0.05$. The ANOVA model performed on approach construction costs was

$$\log_{10} A_{ijk} = \mu + L_i + E_j + LE_{ij} + \varepsilon_{(ij)k}$$

where

A_{ijk} = actual approach construction cost,
μ = the grand mean,
L_i = approach length,
E_j = amount of earthwork,
LE_{ij} = interaction of approach length by amount of earthwork, and
$\varepsilon_{(ij)k}$ = the error term.

Two main factors were treated as fixed effects. Table 9 shows the ANOVA table for this model. It was found that the interaction of two factors was not significant (P-value = 0.614). Two main effects were, however, significant at a 5 percent level. This implied that two factors, approach length and approach earthwork, can be used as grouping factors for estimating approach construction costs.

Table 8 also shows 95 percent confidence intervals of the cell means. The measurement unit of cost is $1,000 in this table. It is shown that the cells in the diagonal position provide the best estimates. Cells with a small sample size had wider confidence intervals. Although this linguistic grouping approach was somewhat coarse, results appeared to be promising for making initial estimates of approach construction costs.

SUMMARY AND CONCLUSION

Results of statistical analyses on costs of bridge superstructure, substructure, and approach construction, which can be used to make initial cost estimates, have been discussed in this paper. Unit structure costs are often used to estimate total structure costs. FHWA requires the state to submit unit structure costs by highway system type and by superstructure type. The replacement cost analysis tested whether this classification could be adequate to account for variations in unit costs caused by the site-specific nature of bridge construction.

As for superstructure construction costs, the analysis was conducted only for primary and secondary highway systems. The difference in the mean unit costs for these two types of highway systems was not statistically significant. Adequate samples were not available for other highway systems, that is, Interstate, urban highway, and off-system roads.

Currently, substructure type is not used to categorize unit structure costs. However, it was found that substructure type significantly affects unit substructure and unit total structure costs. In this analysis, costs were considered in terms of two substructure types: with solid-stem piers and pile-type piers. This simple two-type grouping considerably improves the accuracy of estimates of substructure construction costs.

The analysis conducted on approach construction costs showed that the prediction of approach costs could be improved by grouping such costs in terms of approach length and amount of earthwork. For instance, the mean approach cost of a short approach with a small amount of earthwork was $80,000 and its confidence interval was $20,000. As the approach road becomes longer and the amount of earthwork becomes large, the confidence interval increases, indicating that there was more variation in such large construction.

In this paper the emphasis is on the use of statistical principles to assess the accuracy of unit bridge costs to be used for estimating future bridge construction costs. Often, average values are used as representative costs of that group, but unless the deviation of costs is known, one is not sure about their precision. Standard errors of the mean and 95 percent confidence intervals of the mean unit costs should help engineers and inspectors understand how much variability might be expected when average values are used.

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