Microcomputer-Based Culvert Ranking System

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The efficient use of limited resources is a problem that faces every local government. These governments have large investments in local roadways, bridges, and culverts. No management system has been developed for culvert systems. The development of a ranking system for culverts found on local agency systems is presented. Cost models are developed to identify major contributors to user and agency costs. On the basis of the cost models, a working dBase III Plus™ microcomputer software package was developed to evaluate culvert systems of local agencies. The results of the proposed system were compared with existing culvert replacement strategies with good agreement.

Culverts are an integral part of any highway system.The enormous public investment in these structures demands that they be properly managed and receive timely and cost-effective maintenance, rehabilitation, and replacement. At present, pavement and bridge management systems have been developed for roadway and bridge systems, respectively. In most local agencies there are more culverts than bridges. However, culvert systems, by their nature, are significantly different from pavement or bridge systems. No management system has been developed for culvert systems.

A true culvert management system will be complex. It must be able to perform a complete functional evaluation of each culvert and identify the optimum options for maintenance, rehabilitation, or replacement. Significant resources will be required to advance current technologies to this level; however, the long-term savings in public costs would justify the expense.

The first step toward a comprehensive culvert management system is the development of a system to give a relative ranking to each culvert in the agency's system. The methodology for developing such a system is presented. Whereas the approaches used on existing bridge management systems are evaluated, cost models for culverts are developed to identify major contributors to user and, for some situations, agency costs. The methodology is used to develop a computer software system that uses a data base management system. To demonstrate the applicability of the data base system, microcomputer, and the ranking system, a culvert system of a local agency is evaluated. The results of the proposed system are compared with existing culvert replacement strategies.

LITERATURE REVIEW

After a review of the literature, it was determined that little information has been developed and reported for incorporation into a culvert management or ranking system. Culverts have properties similar to bridges, but they also have significant differences. Several bridge management systems have been developed. Because of the similarities between management of culverts and bridges, a brief discussion of the development of bridge management systems is presented.

A management system could be defined generally as any system or series of engineering and management functions that, taken together, result in the actions necessary to manage the system. For bridges or culverts, the actions may include evaluation of problems, selection of improvement projects, and the programming and initiation of specific projects.

Alternatively, the actions could be inventory and inspection of culverts or bridges, evaluation of priorities, selection and programming of projects, and improvement of structures.

In the United States, the approach taken to culvert or bridge management ranges from informal to formal. Most bridge management system (BMS) developers encourage development of a comprehensive system that tends toward the formal end of the spectrum. These management systems are more likely to result in sound, cost-effective decisions. They provide formal procedures to ensure consistency in the decision-making process; analytical models to evaluate needs, priorities, and options; and an adequate data base to support the analytical models. The primary objective of most management systems is to assist the program manager in setting the needs for resources and to use the resources available in a cost-effective manner while meeting current and future needs.

A bridge ranking system was developed in Kansas using a modified version of the Delphi technique (*1*), which was originally developed by the Rand Corporation in the late 1940s for arriving at a consensus of experts. The Kansas Department of Transportation (KDOT) organized a Delphi panel consisting of 25 key individuals from KDOT (average length of service of 26 years) to make the necessary assessments for development of priority-ranking formulas. This system may work well for large agencies, but a local agency usually has only one or two experts. Thus, the approach may not be applicable to the implementation of a bridge or culvert management system by a local agency.

One of the first formulations of the level-of-service concept for traffic was accomplished at North Carolina State University by Johnston and Zia (*2*) for the North Carolina Department of Transportation. The purpose of the research was to establish level-of-service requirements to evaluate the adequacy of North Carolina bridges. Level-of-service goals were set for various bridge parameters such as load capacity, deck width, and vertical clearances. The goals are target values for selected bridge characteristics. They were varied on the basis

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of highway functional classification, traffic volume, and other factors. The goals were set with the recognition that widely varying traffic needs exist throughout the highway system and that many bridges on local roads can adequately serve traffic needs with lower load capacities and geometric standards than would be necessary for bridges on heavily traveled highways. The degree to which a bridge is deficient can be measured by comparing bridge characteristics with level-of-service goals. Shortfalls from the goals determine the type and extent of improvement needed. The shortfalls are useful for comparing bridge needs and setting improvement priorities.

Several versions of the early North Carolina system were reviewed, including those of Nebraska (*3*), Virginia (*4*), and Pennsylvania (*5*). These systems were essentially modifications of the North Carolina system except that each state varied weighting factors to meet its own criteria.

Several BMSs were studied before the current culvert management system—CMS—was developed. One was that of Hudson et al. (*6*), which reviewed the management needs associated with the nation's bridges and investigated practices of selected state departments of transportation in bridge management activities at the network level. This background provided the framework for a generic BMS followed by a conceptual model BMS. This system is currently being developed for bridges but not culverts.

Later versions of BMSs have begun to incorporate life cycle cost and incremental benefit-cost analysis (*7*). The objective of these analyses is to identify projects that produce benefits greatly in excess of their cost. Deterioration models are being studied to predict deterioration rates of new bridges or bridges that receive various rehabilitation or maintenance treatments (*8*). These methods may provide some advantages for determining which projects would maximize benefits; however, cost data are required for a large number of alternatives.

In conclusion, no BMS can be directly applied to culverts because BMSs do not consider the hydraulic function of culverts, most BMSs are not microcomputer oriented, and other BMSs require large resources of experienced people (e.g., Delphi) or data.

RANKING FORMULA DEVELOPMENT

A methodology is presented for developing the ranking formula for use in a culvert management system. The level-of-service goal concept, originally developed by Johnston and Zia (*2*) for BMSs, was selected as the basis for the proposed culvert management system. Level-of-service goals are set for each culvert parameter. The goals are target values used to assess culvert adequacy and may vary on the basis of highway functional classification, traffic volume, and other factors. When a culvert parameter fails to meet its service goal, a deficiency is incurred. The equation describing this relationship is

$$\text{Deficiency points} = \text{actual condition} - \text{goal condition} \qquad (1)$$

Four priority-ranking formulas were developed for use in the culvert management system. Development of the formulas involved identification of factors that control user and agency costs: load capacity, hydraulic capacity, width deficiency, and maintenance costs. The factors were selected on the basis of experience and discussions with engineers and supervisors.

The objective of the priority-ranking formulas is to develop a numerical value for each culvert in the system. The priority-ranking formulas are a function of culvert parameters. The simplest have the following form:

$$\text{Deficiency points} = \sum K_i f_i(a, b, c, d) \qquad (2)$$

where

K_i = weighting factors,
$f_i(a, b, c, d)$ = priority-ranking formulas, and
a, b, c, d = culvert parameters.

Before the ranking formula can be implemented, parameters must be collected for all culverts in the system. If the approach is to work, all culvert parameters must be accurate and consistent.

The weighting factors provide a means to give relative importance to each of the ranking formulas. They also provide flexibility and permit modification of the system to consider local conditions. For example, if narrow culverts are important local considerations, the weighting factor for the width deficiency ranking formula may be increased.

Before the analytical procedures used in the development of the four priority-ranking formulas are presented, the development of a traffic model must be presented. Because one of the goals of the project was to make the system applicable to local systems, the traffic profile selected was based on a traffic weight study conducted by KDOT (*9*, pp. 33–36). The data at seven rural stations were considered. The study provided data on the distribution by type and weight of all traffic measured. There were 29 combinations of loaded and empty vehicles. Operating costs were assigned to each vehicle type on the basis of estimated 1988 costs. A more detailed discussion of the traffic and cost model used is given elsewhere (*10*).

LOAD CAPACITY RANKING FORMULA

User costs are associated with a culvert with a load capacity less than the goal because the user must drive extra miles around the posted culvert. The costs occur every day that the deficiency remains. To establish the load capacity ranking formula, the cost model previously discussed was developed to relate user cost to insufficient load capacity.

A linear regression model was used to represent user costs for culvert capacities between 3 and 37 tons. The structure was assumed to be closed if the service load dropped below 3 tons. The equation defining the relationship between unit user cost (in dollars) per day-mile-ADT and insufficient load capacity is

$$\text{Cost/day-mile-ADT} = (-0.0029 * \text{SV}) + 0.1053 \qquad (3)$$

When the load capacity cost model is substituted into the deficiency points equation, the load capacity ranking formula becomes

$$\text{CP} = \text{WC} * (\text{CG} - \text{SV})/345 * \text{ADT} * \text{DL} \qquad (4)$$

where

CP = capacity priority,
WC = load capacity weighting factor,
CG = capacity goal (tons),
SV = single vehicle posting (tons),
ADT = average daily traffic, and
DL = detour length (mi).

CP may not be less than 0.

Hydraulic Capacity Ranking Formula

User costs are associated with the hydraulic capacity of a culvert because of the extra mileage accumulated during detour around a flooded culvert. Hydraulic-related costs occur only on flood days. A culvert with insufficient hydraulic capacity may result in recurring agency costs due to flood damage to the roadway, structure, or adjacent property. The following cost model was developed for user and agency costs due to insufficient hydraulic capacity.

The percentage of ADT affected by insufficient hydraulic capacity was established from the same vehicle data used to develop the load capacity ranking formula. In this case, if a culvert cannot support a vehicle of a particular weight, then, theoretically, the vehicle should not be affected by flooding of the culvert. In this way, each detoured vehicle is counted only once for a culvert deficiency. On the basis of this assumption, the percentage of ADT affected by insufficient hydraulic capacity is a function of load capacity.

The user costs for each vehicle type developed for the load capacity ranking formula were used to develop a cost model to describe hydraulic-related user costs. An operating cost was assigned to each type of vehicle affected. An exponential curve was developed to best fit the data and relate the unit user cost per day-mile-ADT and insufficient hydraulic capacity. The relationship is

$$\text{Cost/day-mile-ADT} = 0.062 * (SV - 3)^{0.30} \quad (5)$$

where SV is as previously defined.

Agency costs considered in this ranking formula are the cost per flood per day and the number of flood days per year. The average cost per flood is the cost, to the agency, of flood damage to the roadway, structure, and adjacent property at a particular culvert site. The number of flood days per year is the number of days each year a particular culvert site floods. When the hydraulic capacity cost model is substituted into the deficiency points equation, the hydraulic ranking formula becomes

$$HP = WH * (NF - NG)/365 * [(KF * ADT * DLh) + \$/\text{flood}] \quad (6)$$

where

HP = hydraulic priority,
WH = hydraulic capacity weighting factor,
NF = number of flood days per year,
NG = goal for number of flood days per year,
KF = $0.062 * (SV - 3)^{0.30}$,
DLh = detour length due to flooding (mi), and
$/flood = average damage cost per flood day.

HP may not be less than 0.

Width Deficiency Ranking Formula

User costs related to the width deficiency of a culvert result from accidents. Width-related costs occur every day until the deficiency is corrected. Narrow culverts contribute to single-vehicle collisions involving pedestrians or the culvert structure and to multiple-vehicle collisions involving approaching or passing vehicles. Resulting user costs include property damage, injury, and loss of life. Agency costs include repair of structural damage and higher insurance premiums. To establish the width deficiency ranking formula, a cost model was developed to relate cost to insufficient culvert width.

The first step was to establish a relationship between culvert with deficiency and related accidents. A study of bridge width and safety (*11*) provided information to derive a relationship between the number of accidents per million vehicles and the relative bridge width. The relative bridge width is the difference between the traveled-way width and the bridge width. It was believed that this best represents the situations found at narrow, rural culvert sites. The equation is

$$\text{Number of accidents per million vehicles} = (0.0022 * WD^2) - (0.061 * WD) + 0.5 \quad (7)$$

where WD is the relative bridge width (ft).

The traveled-way width is the combined width of the lanes only crossing the structure (shoulders are not included). If the culvert is wider than the traveled way, the relative culvert width is a positive value. If the culvert is narrower than the traveled way, the relative culvert width is a negative value.

The second step in the development of the cost model was to establish an appropriate cost per accident. A cost of $48,430 was chosen on the basis of 1985 nationwide accident cost data (*12*). That was the value for rural non-federal-aid systems, and it best represents a rural local agency road system. The value was verified by using another technique given elsewhere (*13*). The equation defining the relationship between unit user cost per day-ft-ADT and insufficient culvert width is

$$\text{Cost/day-ft-ADT} = 0.048430 * ADT * [(0.0022 * WD^2) - (0.061 * WD) + 0.5] \quad (8)$$

When the width deficiency cost model is substituted into the deficiency points equation, the width deficiency ranking formula becomes

$$WP = WW * [(WD^2 - WDG^2)/9{,}380 - (WD - WDG)/338] * ADT \quad (9)$$

where

WP = width priority,

WW = width deficiency weighting factor, and
WDG = relative culvert width goal (ft).

WP may not be less than 0.

Maintenance Ranking Formula

Agency costs related to maintenance of a culvert result from blockage of a waterway by debris and sediment. Routine maintenance for culverts consists primarily of the removal of obstructions and the repair of erosion and scour. Prevention of joint leakage may be critical in culverts bedded in pipeable soils to prevent undermining and loss of support. The maintenance cost model was based on yearly maintenance costs incurred by the agency for each structure. When the maintenance cost model is substituted into the deficiency points equation, the maintenance ranking formula becomes

$$MP = WM * (MC - MG)/365 \quad (10)$$

where

MP = maintenance priority,
WM = maintenance weighting factor,
MC = maintenance cost ($/year), and
MG = maintenance goal ($/year).

MP may not be less than 0.

The ranking formulas developed for this culvert management system were assembled into a deficiency points equation. The equation represents the total combined user-agency cost per day for a given culvert. For each culvert, the deficiency points (DP) are the sum of four culvert ranking formulas: load capacity, hydraulic capacity, width deficiency, and maintenance. The deficiency points are calculated on the basis of the following formula:

$$DP = CP + HP + WP + MP \quad (11)$$

Weighting Factors

Weighting factors allow the user to change the relative importance of the various ranking formulas. Since the ranking formulas are all based on estimated costs, the recommended value for all weighting factors is 1.0. If specific local considerations are important, the weighting factor may be increased or decreased. However, the weighting factors should not be changed indiscriminately. Because the basis of the formulas are user and agency costs, a change in the weighting factors has the effect of reducing or increasing the costs associated with each priority formula. For example, it could be argued that load capacity is not important because culverts in the agency are not posted. However, there is a risk to the public and the agency in case of structural failure of some culverts. Therefore, the weighting factor for LC should be set equal to zero for this extreme case.

Culvert Parameters

The proposed deficiency points ranking formula contains four weighting factors, four ranking formulas, and eight basic culvert parameters. The culvert parameters are posted weight (tons), ADT, relative width (ft), detour length, flood detour length, flood days per year, average cost per day per flood, and maintenance costs per year.

The development of such a system is a series of compromises. If every conceivable culvert parameter were used in the priority-ranking formulas, the data collection effort would become significant. Even for smaller culvert systems, this approach could become an unwise use of limited resources. Because the objective of the culvert management system is to set priorities and get a relative ranking of the system's culverts, a more logical approach is to minimize the number of culvert parameters collected.

The number of deficiency points for each culvert is always greater than or equal to zero. Obviously, the worst culvert in the system will have the largest number of deficiency points, and the best culverts in the system will have no deficiency points.

SOFTWARE

To assist in verifying that the proposed system works, a comprehensive data base software system was developed. Written in dBASE III™, CMS provides for the creation of the required data bases, conducts certain hydraulic analyses, calculates the deficiency points for each culvert, and provides for output in several formats.

Before CMS will work, three data bases must be created. The first contains the culvert parameters, the second defines the level-of-service goals, and the third defines the weighting factors. For first-time users, default data bases are provided.

CMS is a menu-driven system. Step-by-step execution of individual menu items gives the user full control of program flow and analysis. The user reaches the appropriate module by working through the menu structure shown in Figure 1. The numbers above each box are the responses the user should make to get to the desired menu. The user may always move to the previous menu by returning to any menu and pressing 9.

By selecting the create option, the user may add data to the culvert, level-of-service goal, or weighting factor data base. By selecting the merge/modify option, the user may merge an existing culvert data base or modify existing data in the culvert, level-of-service goals, or weighting factor data bases. By selecting the culvert ranking option, the user may rank all culverts in the system. Obviously, before culverts are ranked, data for the culverts must be collected and entered into the culvert data base. The culvert ranking results may be viewed on the screen or sent to the printer using the output results option.

The user may select the hydraulics option to perform simple hydraulic analysis of existing culverts. Two analysis procedures are supported by CMS. The rational method permits the user to input respective land use areas and their corresponding runoff coefficients. After the rainfall intensity is entered, the peak flow rate for the drainage basin is calculated. The second analysis procedure is based on U.S. Geological Survey data for calculating the peak flow rates on unregulated streams in Kansas (*14*). A regression equation based on return period, drainage area, 24-hr rainfall depth, and main channel slope was implemented in the software.

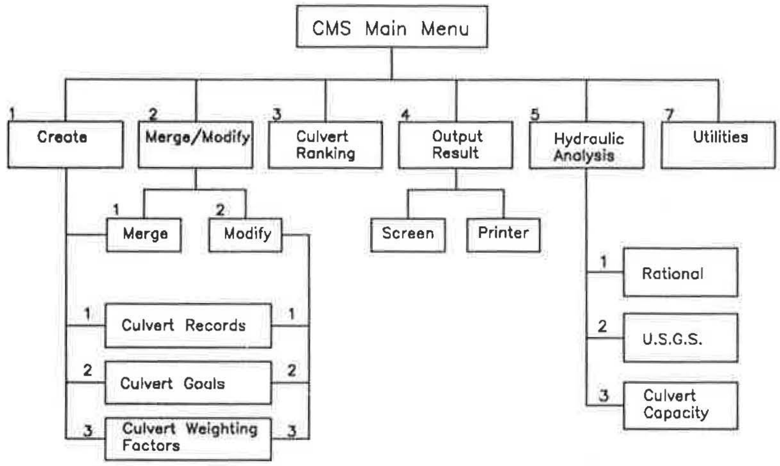

FIGURE 1 CMS menu structure.

A simple culvert capacity calculator is also supported in the hydraulics option. This determines the culvert capacity by multiplying the open end area by an average velocity. The coefficients required to conduct any of the hydraulics options are automatically stored in the culvert data base.

The utilities option may be selected to configure CMS and to designate specific data base file names, agency name, and paper width for printer output.

APPLICATION TO A LOCAL CULVERT SYSTEM

To illustrate the application of the proposed system to a local agency culvert system, the culverts of a local county were evaluated. The county, in Kansas, is located near a growing major metropolitan area. However, many of the county culverts are on rural roads.

To provide a feel for the county's culvert system status at time of evaluation the following description is provided. There were 1,459 culverts in the system. The distribution of culverts by type is as follows: 77 were corrugated metal arch, 676 were corrugated metal pipe, 94 were concrete arch, 346 were reinforced concrete box, 96 were reinforced concrete pipe, 89 were simple span, 69 were stone arch, 1 was stone box, and 11 were of an unknown variety.

The agency had previously developed a good data base for its culvert system. However, some additional assumptions and modifications were needed to evaluate the system. Forty-four culverts had been load rated. Because CMS requires a load rating for each culvert, a load rating was assigned to all other culverts on the basis of the agency's structural condition rating system. New culverts and older culverts with no problems were rated at 16 tons. Culverts with minor structural problems were rated at 13 tons, those with intermediate structural problems were rated at 8 tons, those with major structural problems were rated at 3 tons, and failed culverts were rated at 0 tons. Fifteen culverts were closed but were included in the totals.

Four hundred seventy culverts were not adequate to handle the flow requirements of their particular drainage basin. Estimates for the number of flood days per year and cost per flood for each culvert were made on the basis of agency data. If the culvert's hydraulic capacity was adequate to handle the flow, the number of flood days per year was set equal to zero. If the flow capacity was inadequate, 1 flood day per year was assigned at cost of $1,000 per flood. In the case of structures being replaced by structures with twice the capacity, 2 flood days per year were assigned at a cost of $1,000 per flood. Two hundred eighty-seven culverts were narrower than the traveled roadway. The relative culvert width ranged from 0 to −10 ft. The average relative culvert width was −0.6 ft.

One hundred forty-two culverts required major maintenance. Estimates of the yearly cost of maintenance for each culvert were made using agency data. Culverts requiring no, minor, medium, or major maintenance were assigned maintenance costs of $0, $200, $400, or $600 per year, respectively.

The highway classifications, at time of evaluation, were not available. All highway classifications were assumed to be "local." The ADT counts varied from 0 to 4,107. Ninety percent of the ADTs were below 1,000. The average ADT was 376.

Weighting Factors and Level-of-Service Goals

Whereas any number of highway function classifications could be defined, all classifications for this system were defined as "local." For all ADT ranges, the load capacity goal was set at 16 tons, the hydraulic capacity goal was set at 0 flood days per year, the relative width goal was set at 0 ft, and the maintenance goal was set at $0 per year. All weighting factors used in this application were set equal to 1.0.

Results

The 1,459 culverts were evaluated using a 12 MHz 80286 microcomputer. The analysis took approximately 20 min, including the calculation of all deficiency points and placement of the culverts in descending order on the basis of the deficiency points. Because most local agency culvert systems are approximately this size, a microcomputer with the software developed in this project can handle culvert systems of this size.

For all culverts, the number of deficiency points ranged from 0 to 244. Five hundred forty-five culverts had no deficiency points. The maximum number of deficiency points (for a culvert with the highest ADT totally deficient in load capacity, hydraulic capacity, relative width, and maintenance) would have been approximately 520.

For culverts with relatively low load capacity values, culverts with high ADTs had the higher number of deficiency points. The 10 culverts with the highest number of deficiency points had high ADTs. The ADTs varied between 724 and 2,207. The operating rating of these culverts varied between 0 and 8 tons. Six out of the top 10 culverts were hydraulically inadequate. The relative culvert widths of the first 10 culverts varied between 0 and 10 ft. Seven of the first 10 culverts had maintenance problems.

The results were then compared with the local agency's previously developed comprehensive culvert replacement program. In this program two agency persons (APs) independently ranked the culvert system. AP1 is an engineer familiar with the technical aspects of the system, whereas AP2 is an engineer familiar with management responsibilities for the system. CMS identified 32 of AP1's 50 top culverts (see Figure 2). The diagonal line is where data points would lie if the CMS ranking agreed perfectly with the agency ranking. Data points above the diagonal line represent culverts rated more critical by CMS than by AP1, and vice versa. The data points along the top of Figure 2 represent culverts ranked by CMS in the top 50 but ranked greater than 50 by AP1. The culverts that were not in the top 50 of AP1's ranking but were ranked critical by CMS tended to have reduced load capacity. Because the load capacity for these culverts was arbitrarily assigned and may be inaccurate, it is recommended that they be load rated. If it is assumed that these culverts drop out of the top 50 when properly load rated, a better correlation between CMS results and AP1 occurs (see Figure 3).

CMS identified only 23 of the top 50 culverts identified by AP2 (see Figure 4). AP2's ranking appears to place more importance on relative culvert width. This may reflect the safety concerns of a system manager. If AP2 had assigned more importance to load capacity, the correlation between the rankings by CMS and AP2 would have been better. If an actual load rating could be done for all culverts, a better correlation between CMS and AP2 would occur. Figure 5 shows the correlation if all culverts ranked high by CMS were determined adequate when load rated. Except for specific instances, the culverts chosen by CMS were scheduled for early replacement, were under construction, or were replaced.

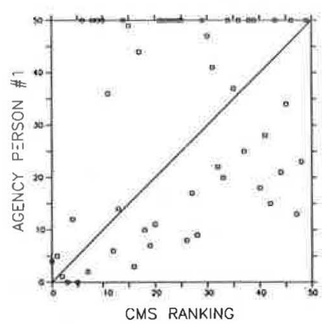

FIGURE 2 CMS compared with AP1 ranking of top 50 culverts.

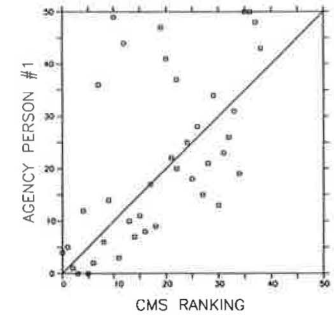

FIGURE 3 Removal of AP1's noncritical culverts improves correlation with CMS.

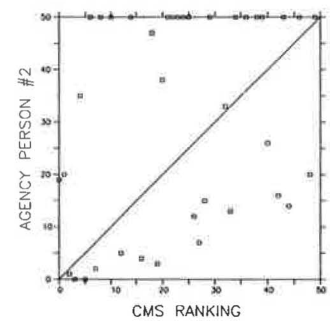

FIGURE 4 CMS compared with AP2 ranking of top 50 culverts.

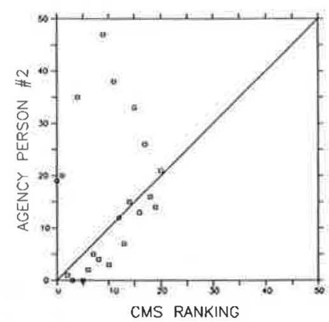

FIGURE 5 Correlation of CMS and AP2 rankings if all culverts ranked high by CMS were determined adequate when load rated.

Because 1,459 culverts were considered in the system, remarkable correlation occurred between the CMS system and the independent ranking by local APs. Several observations can be made. The need for accurate data is imperative. Errors in culvert data may cause obvious discrepancies. The cost model developed appears to give reasonable results when compared with the existing construction program. Because CMS is cost based, system administrators can evaluate the total system over a period of time. In 5 years, a lower average number of deficiency points would indicate an overall improvement of the system.

SUMMARY AND CONCLUSIONS

A ranking system for culverts found on local agency road systems was developed. Cost models were developed to identify major contributors to user and agency costs. A working dBase III Plus™ microcomputer program was developed using this cost model information. The program was used to evaluate a culvert system of a local county. The results of the proposed system were compared with existing culvert replacement strategies.

The results of the culvert management system studies support the following conclusions:

1. A culvert management system based on a cost approach is practical and gives good rankings of a local culvert system.
2. Important cost factors, in order of importance, were load capacity, relative width deficiency, hydraulic capacity, and maintenance.
3. Microcomputers can analyze local culvert systems. A working dBase™ microcomputer program was developed using cost model information. The time required to develop a culvert replacement program with the use of a culvert management system was significantly lower than with the manual selection process.
4. The system developed provides flexibility to local agencies by permitting local definition of level-of-service goals and weighting factors.
5. A measure of the system's capability is a steady decline of a system's average deficiency points.

To fully implement a culvert management system, it will be necessary to evaluate life cycle costs, deterioration models for each culvert type, and effects of further maintenance strategies. With this more comprehensive management approach, better selection of culvert maintenance projects may occur, and maintenance engineers may be able to evaluate the consequences of resource allocation during the budgeting process.

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