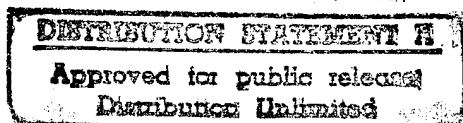# IDENTIFICATION AND ANALYSIS OF GENERAL

DECISION SUPPORT PRINCIPLES FOR CATEGORY

SPECIFIC MAINTENANCE MANAGEMENT SYSTEMS

WITH SPECIAL CONSIDERATION FOR THE FUTURE

DEVELOPMENT OF AN EARTHEN EMBANKMENT DAM

MANAGEMENT SYSTEM

An Engineering Report

by

Tom Hoenstine

Submitted to the Graduate Advisory Committee of

Texas A&M University

in partial fulfillment of the requirement for the degree of

MASTER OF ENGINEERING

July 1996   DTIC QUALITY INSPECTED 3

Major Subject: Construction Engineering

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Executive Summary

Infrastructure Maintenance Management Systems are automated decision support tools which aid infrastructure managers in optimizing limited maintenance resources. As America's infrastructure continues to age and the government's maintenance budget gets tighter and tighter, Infrastructure Maintenance Management Systems are growing in importance. These systems are designed to assist managers by organizing information and predicting future performance and future costs. Infrastructure Maintenance Management Systems are designed to assist one of two levels of management: project and network. Project level management requires the most detailed information. At this level specific maintenance response activities are identified for every discrepancy on each item of infrastructure. Network level management focuses on the development of policies and budgets for certain areas or specific systems.

Three different types of Infrastructure Maintenance Management Systems exist:

1. Maintenance Management Systems that are designed at the project level and include the detailed tracking of maintenance crews and repair parts necessary for managing the maintenance activities of a single facility or factory;

2. Category-Specific Management Systems that track costs and predict future expenditures and budgets for a single category of infrastructure such as pavements, bridges or waste water distribution systems. These systems can work at the project or network level;

3. Infrastructure Management Systems that aid in establishing maintenance budgets for communities, agencies or regions. They include multiple categories of infrastructure and are designed for use at the network level of management.

This paper develops the conceptual framework necessary for creating a category-specific system that manages maintenance and repair work for embankment dams. The critical elements for establishing an Embankment Dam Management System (EDMS) are identified and analyzed through evaluating current literature on existing systems and theories. Many pavement and bridge management systems exist in varying degrees of sophistication. The essential elements include:

1. Inventory and Inspection,
2. Condition Assessment,
3. Load Analysis,
4. Performance Prediction,
5. Scope of Work/Cost Analysis,
6. Budgeting/ Work Prioritization.

These elements are interdependent and must be developed in conjunction with each other. The inventory/inspection procedures must capture the necessary information to conduct the condition assessment, predict future performance and develop a scope of work. The condition assessment establishes the current condition and drives the performance prediction. The performance prediction justifies the scope of work for future maintenance requirements. Based on the scope of work and by analyzing possible alternative strategies, the system is able to establish maintenance priorities and predict required maintenance budgets for various maintenance strategies. This entire process is generated through models and equations that are calibrated with historic data in so far as is possible in order to predict the future as accurately as possible. The most effective EDMS can be developed by taking advantage of the lessons learned from these existing systems and modifying current models to meet the needs and peculiarities of managing embankment dams.

I. Introduction:

Most of the infrastructure in the United States is in poor condition and in serious need of repair. Many infrastructure items have not only surpassed their initial design life but many are also suffering from years of neglect (Rens, 1994). This infrastructure includes any construction which provides the framework for transportation or the base from which businesses, communities and cities operate, including roadways, bridges, power distribution systems, facilities, water distribution systems and flood control/waterway navigation systems. Caught in a period of monetary crisis, the United States government, over the last thirty years, has been forced to change its infrastructure policy. The nation has moved from an attitude of "replace not renovate," where the usual approach to rehabilitation was to tear down and rebuild, to the current practice of maintaining the existing infrastructure for as long as possible by developing the most effective means of allocating maintenance and repair budgets. Federal and local governments and corporations alike are all working at improving management techniques to develop the most efficient means of extending the life of the existing infrastructure. The problem is steadily building to crisis level (Schewen, 1995). In the article, "New Frontiers in Civil Engineering," Poggemeyer states that experts estimate that it will take $1 trillion by the year 2000 and $3 trillion by 2010 just to replace and repair the current federally owned infrastructure in the United States. The problem is further complicated by the fact that net investment in public works by federal, state, and local governments has dropped from 2.3% of the Gross National Product (GNP) in 1960, to a mere 0.4% of the GNP in 1984. Poggemeyer further states that while the investment in infrastructure is steadily declining, simultaneously, the need for and dependency on operational, efficient infrastructure is continuously growing.

With the computer revolution and the many associated technological advances in the capabilities of personal computers, many organizations are turning to computer expert systems to aid in developing effective maintenance management strategies. Expert computer systems are being created to aid in every level of maintenance management. The goal of these decision support systems is to aid the user in optimizing the value of maintenance funds and to prioritize maintenance activities given the limited resources allocated to infrastructure maintenance.

A. Background:

Infrastructure maintenance management is a subject that is rapidly growing in importance as most of the nation's infrastructure has surpassed its initial design life and, at the same time, competing monetary demands are causing maintenance budgets to steadily shrink. Recent advances in technology have enabled computer decision support systems to play a more vital role in assisting decision makers in allocating the limited resources designated for infrastructure maintenance and repair (Person, 1986). Most factories implement some kind of automated maintenance management system and every state and major city department of transportation is required by the 1991 Intermodal Surface Transportation Efficiency Act to employ pavement and bridge management systems. Dams are an item of infrastructure that are becoming increasingly more critical, as one study showed that nearly 9000 dams are classified as "high hazard" and therefore pose a serious threat to public safety (Poggemeyer, 1988). Current research has focused on developing a detailed, systematic condition assessment of embankment dams, but little has been done to develop a complete maintenance management system for these items of infrastructure.

B. Study

1. Overview

In the article "Maintenance Management Information Systems," Paul Tomlingson (1992) suggests that the process of establishing an effective maintenance management information system includes four necessary phases which must take place sequentially:

a. Conceptualization: Identifying the needs and factors that will influence the development of the system and determining the required support for the system;

b. Development: Creating a plan of action for bringing the conceptualized information system to life considering the practical aspects of collecting field data, processing it, and converting it into useful information;

c. Implementation: Integrating the newly developed system into the organization and handing it over to the people who will use it;

d. Utilization: Accomplishing maintenance improvement objectives by utilizing information from the system.

This study concentrates on the conceptualization phase, including the development of the necessary elements and the essential principles behind these elements. Nothing has been written about applying a decision support system to the management of embankment dams. However the same elements that are being incorporated into pavements, bridges, railroads and sewage management systems can be modified and applied to establish an Embankment Dam Maintenance System (EDMS). While the basic principles behind the elements can be established now, the necessary modeling and detailed analysis will require significant research and validation before they can be effectively applied to an EDMS.

These procedures must be addressed during the development phase. This study focuses on the identification and definition of the necessary elements for an effective EDMS.

2. Methodology:

This study analyzes several existing category-specific Infrastructure Maintenance Management Systems in order to determine the essential elements for a complete system. The paper will identify the issues and requirements that must be addressed in order to implement an effective decision support system for embankment dams. The proposed Embankment Dam Management System (EDMS) will incorporate the systematic condition assessment developed by Andersen and Torrey III (1995). The system must be capable of working in conjunction with the established condition assessment to assist maintenance management decisions for embankment dams by:

1. Predicting current and future maintenance costs; and

2. Prioritizing maintenance activities.

II. Management System Overview:

A. Definitions

1. Infrastructure Maintenance Management Systems:

Three distinct levels of Infrastructure Maintenance Management Systems exist. The levels are defined by the number of items and specific categories of infrastructure that are maintained within the system. The three levels include:

1. Maintenance Management Systems

2. Category-Specific Infrastructure Management Systems

3. Infrastructure Management Systems

The most detailed and specific system is a Maintenance Management System designed as a decision support tool for the maintenance manager of a specific facility. Maintenance schedules are developed to optimize the service life of specific machines. Ordered parts are tracked from request through delivery and installation. These systems are capable of tracking costs and maintenance work by each employee and determining which machines require the most support. Most facilities have some sort of maintenance management decision support tools and many different software programs exist that accomplish these objectives. The literature describing these systems is limited to articles that explain how one specific system has been effectively implemented by a certain company or agency.

The next level of infrastructure maintenance management is the decision support tool designed to facilitate budget decisions regarding a specific category of infrastructure such as pavements, bridges or railways. These systems generally take on the name of the category for which they were designed such as Pavement Management Systems (PMS), and Bridge Management Systems (BMS). These systems require much more scientific analysis as they attempt to rank order maintenance requirements, predict costs, prioritize work and project budgets for a specific category of infrastructure. The system may maintain as little as the road network of a small town or be as extensive as maintaining all the bridges in the state of Virginia. Many papers have been published regarding these systems

as researchers struggle with defining performance ratings, predicting deterioration and dealing with uncertainty.

The top level of Infrastructure Maintenance Management Systems are Infrastructure Management Systems (IMS). IMS systems are decision support tools for managing an area or jurisdiction which includes two or more categories of infrastructure. These systems are in their infancy and little has been written about them. They must be designed to incorporate a comparison of costs and benefits across the different categories of infrastructure. The last section of this paper addresses some of the emerging ideas and issues in developing an infrastructure management system capable of managing several different items of infrastructure. Ultimately, this is the level at which the most critical decisions will need to be made.

2. Management Decision Levels

Most of the systems acknowledge only two management levels of decision making, project and network. This paper will refer to project and network management levels and not Karaa's three levels. Project level decisions are focused on each of the specific items of infrastructure. This level requires the most detailed information from which specific maintenance response activities are identified for every discrepancy on each item of infrastructure. Network level management is focused developing policies and budgets for certain areas or systems of infrastructure. This level of management focuses on major trends and generalities rather than the specifics.

Infrastructure Management Systems are designed to assist decisions at the network level. Maintenance Management Systems focus at project level decisions. Category-

Specific Management Systems can concentrate on either one of the two levels or, more appropriately address both levels (See Figure 1). However; most of the existing systems are primarily focused on aiding decision making at only one of the two levels.

Figure 1   Management Levels of IMMS Systems
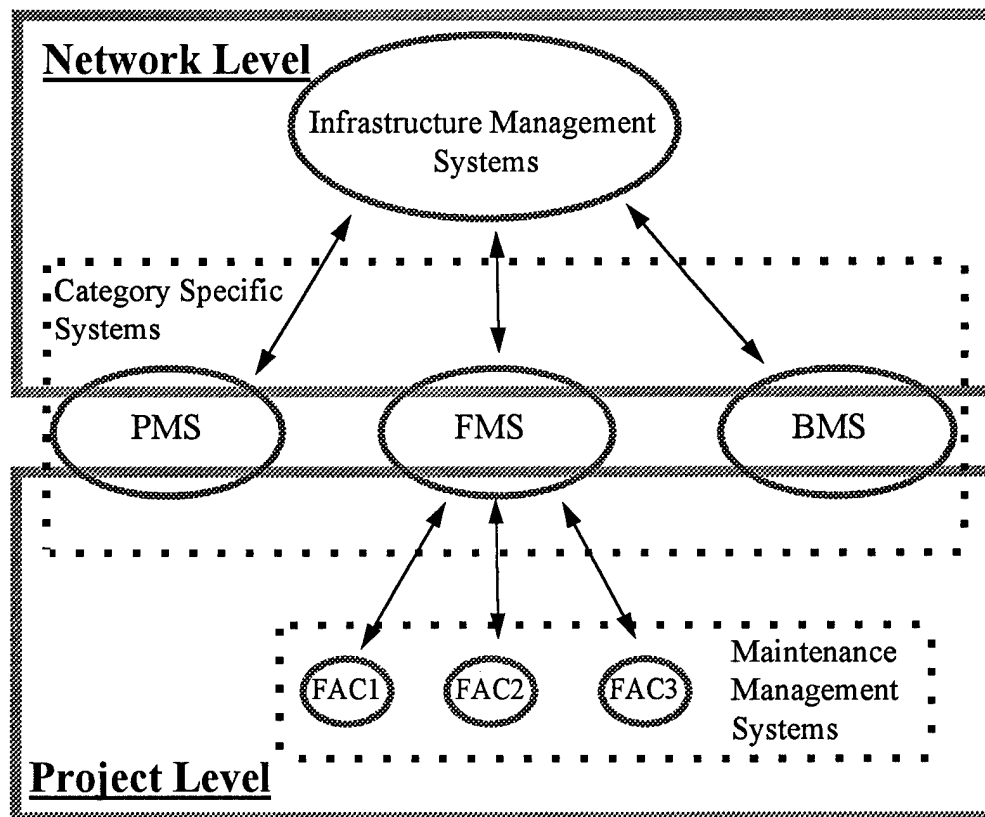
3. Differentiation of Elements and Software Attributes

Most of the literature which addressed the requirements for an effective Infrastructure Maintenance Management System recommended both system software attributes and critical elements that the system must provide. The essential software attributes that encompass and make up the entire computer system describe the architecture of the system. The elements are the critical principles that must be considered and addressed within the

data analysis component of the computer system. Although the software attributes of the system are critical to the system's operation and usefulness, an in-depth analysis of the software attributes is beyond the scope of this paper. This paper will focus on the development of the necessary elements and critical principles that must be included in an Infrastructure Maintenance Management System to make it a valuable asset as a decision support tool.

B. Management System Evolution:

Different types of Infrastructure Maintenance Management Systems have been developed by researchers for various transportation and government agencies for the last 25 years. During this time, several versions of such systems have been implemented. Many of these systems either failed totally or fell well short of achieving their intended goals (Thornton, 1993). Many of the failed systems were either too difficult to implement because of the massive inventory and inspection requirements, or they were ineffective in making accurate predictions of future condition.

Infrastructure Maintenance Management Systems are becoming increasingly more accurate and intricate. The systems have been developed using improved models based on detailed analysis and supported by more valid research using substantially more appropriate data. Much has been written about Infrastructure Maintenance Management Systems; however, most of the articles are written as advertisements to promote specific systems. Many different software programs are available to aid in maintenance management decisions for a single facility or factory. Relatively few of the articles address the necessary software attributes, elements and requirements of an effective management system.

The majority of the literature published in journals addresses system and requirements as applied to the maintenance of road pavements and bridges. This area is critical because not only are repair and maintenance costs excessive (typically 40% of public spending on roads), but deteriorating pavement has a high cost to the general public as it causes excessive damage and safety problems to the vehicles that travel on them (Tavakoli, 1992). The government is extremely concerned with effective pavement and bridge maintenance systems. The federal Intermodal Surface Transportation Efficiency Act (ISTEA) of December 1991 established that in order to get federal funding for highway maintenance, the individual states must implement a pavement management system by January 1993.

C. Current Systems and Methodology:

This section presents a synopsis of the different operating infrastructure management systems that are analyzed in this study. Five different systems are presented: a Waste Water Distribution Management System (WWDMS), three Pavement Management Systems: New Maintenance Computerized System (NEWMAI), Pavement Management System for Small Communities (PMSC), and Integrated Airport Pavement Management System (IAPMS), one Bridge Management System (BMS) and one Rail Management System (RMS). There are more Pavement Management Systems because much more study, analysis and critique has been aimed at pavement systems.

1. Waste Water Distribution Management System (WWDMS)

Fadi A. Karaa (1989) described the essential elements of an Infrastructure Maintenance Management System based on his experience and research with water distribution systems. In the article "Infrastructure Maintenance Management System Development",

Karaa states that there are three separate levels at which maintenance management decisions are made. Effective decisions can only be made when timely and accurate communication flows uninhibited between the management levels. An effective Infrastructure Maintenance Management System must either address all three levels or assist in the flow of information between the three levels. The decision process must be developed from the bottom level up and controlled from the top level down. The three levels include:

a. Strategic Planning Level: Decisions affecting the overall organization are made including determining budget allocations and defining priorities;

b. Operational Control Level: Facility or system level decisions are made concerning inspection methodologies and capital improvement options such as repair, replace or rehabilitate decisions;

c. Tactical Level: This includes the most specific level of detail. The components of the infrastructure system are addressed and analyzed.

Karaa then continues by explaining that the Infrastructure Maintenance Management System (IMMS) must perform five major elements to be totally effective. The elements are described as they apply to a Waste Water Distribution Management System (WWDMS). Karaa states that these elements represent the cornerstone of an effective Infrastructure Maintenance Management System. The specific elements should be adjusted based on the needs and priorities of the managing organization; however, the elements must remain fully integrated. The elements include:

a. Inventory: Developing the database and search engines necessary for the storage, retrieval and manipulation of information regarding the physical descriptions of the facilities and components which comprise the system;

b. Maintenance history: Recording maintenance events, system failures and inspection data to establish a maintenance history and determine the infrastructure's current maintenance trends;

c. Condition Assessment: Evaluating the system based on performance measures and reliability performance dimensions to determine the current level of deterioration;

d. System Performance Prediction: Predicting future performance based on past history and condition assessment. Determine the effects and impact of maintenance decisions on the infrastructure system;

e. Cost and Decision Analysis: Evaluate the different capital improvement measures and develop the annual budget or determine priorities given a specified budget.

Karaa establishes the foundation and key elements for an effective maintenance management system. The elements he identifies are used by all the other systems. The models, historic data and calculations behind the elements are not very well developed. The WWDMS system described in the article relies heavily on assumptions and professional experience to determine condition assessment and make predictions. The system is lacking the required research and historic data necessary to create realistic accurate models. The system includes a element that records maintenance history in order to rate the effectiveness of the maintenance organization. None of the other systems include this element; however they all record the maintenance performed as part of the inventory/inspection element or the cost analysis element. Karaa's levels of management more closely match the different types of Infrastructure Maintenance Management Systems. The other systems address only the project and network levels of management. The important point he makes, though, is that the system must enhance the flow of information through all the levels of management.

2. New Maintenance Computerized System (NEWMAI)

Louis Berger, Jacob Greenstein, Mario Hoffman and Jacob Uzan (1991) describe a Pavement Management System (PMS). In the article "Practical Applications of Models for Pavement Maintenance Management," the authors discuss an operating computerized maintenance system called New Maintenance (NEWMAI). NEWMAI is a second generation system which evolved from the Pavement Management System, PAVER, an earlier mainte-nance system produced by the U.S. Army Corps of Engineers. This system includes five elements which are similar to those described by Karaa but the system's elements are more thoroughly developed than those that Karaa discussed:

a. Pavement-network identification: Accounting for every mile of roadway by breaking down the roadway system into specific identifiable units and locating each seg-ment using a geographic information system (GIS);

b. Pavement-condition survey and rating procedures. Developing the condition as-sessment for each component by using the pavement condition index (PCI) as established by the U. S. Army Corps of Engineers;

c. Distress-prediction models. Predict future performance of the pavement based on sigmoidal regression curves. This analysis takes into account the current condition of the pavement and the results of distresses caused by traffic loads and distresses related to climate and durability;

d. Maintenance activities and strategies. Each type of pavement distress is identi-fied and assigned a corresponding maintenance response. The chosen response is the optimal strategy for removing the distress based on expert engineering experience and judgment;

e. Economic analysis and prioritized maintenance programs. The system incorpo-rates a unit cost for all of the maintenance activities and reports projected annual costs or

prioritizes activities based on a specific budget. A cost-benefit scheme is identified to help determine the economic impact of the maintenance decisions.

The elements of this system are better refined then those in Karaa's WWDMS. The process and principles behind the elements are more thoroughly researched and more clearly explained. The use of the PCI rating for condition assessment is simplistic but nationally accepted as appropriate for pavements. The system's performance prediction element is more sophisticated. Sigmoidal regression curves are used to model deterioration. These curves, however, are based on a limited historic data base. NEWMAI does consider future loads on the pavements as a factor in predicting deterioration, but the future loads, expressed in equivalent single axle loads (ESAL), are primarily educated guesses. The system identifies specific maintenance activities as part of the scope of work element. The least expensive maintenance activity which results in an improved PCI equal to or better than the established target PCI is chosen. This maintenance activity selection is further defined in the scope of work section of this paper. NEWMAI also has the capability of accounting for the typical effectiveness of maintenance repairs as a subroutine in its performance prediction model. The system is also the first to tackle the challenge of assisting in establishing budget priorities (See the budget/prioritization section of this paper). A cost/benefit analysis is calculated based on the predicted vehicle operating costs for the estimated traffic on each road. The required maintenance activities are then prioritized based on results of the cost/benefit analysis.

3. Pavement Management System for Small Communities (PMSC)

Amir Tavakoli, Mitchell S. Lapin and Ludwig (1992) further refine the necessary modules for an effective pavement management system in the article, "PMSC: Pavement

Management System for Small Communities." The PMSC system is specifically designed as a decision-support system for making effective recommendations and decisions about the scheduling and budgeting of various levels of repairs for pavements and roadways within the local transportation network of a small community. This system is described based on eight critical modules which describe six elements and two software attributes:

    a. Inventory: This element remains primarily the same as described in NEWMAI. It is the process of collecting and organizing the essential data necessary to implement the system and make effective management decisions. However, the inventory is improved in one major area, as it uses geographic information systems (GIS) to record the exact location of every pavement in the inventory;

    b. Distress Survey: The process of identifying the type of distress and its severity, and measuring the percentage of area affected. The survey is based on the same pavement condition index (PCI) as NEWMAI, but PMSC adds an additional amplifier to the condition assessment by quantifying the severity of each;

    c. Maintenance and Rehabilitation: This module identifies the best of five general maintenance strategies based on the PCI and pavement type. The strategies include: routine maintenance, preventive maintenance, deferred action, rehabilitation and reconstruction. The system provides the user with the option to review the recommendation and accept it or the strategy selection;

    d. Unit Costs: This module houses the standard unit cost associated with the maintenance and rehabilitation strategies for each of the pavement types. The unit costs are determined by professionals who maintain current cost data on maintenance and construction of road surfaces;

e. Deterioration Rates: Using preset deterioration rates, this module determines what maintenance and rehabilitation strategy a section will receive the following year based on the current year's strategy;

f. Priority Ratings: This module calculates a priority rating for each section based on information input by the user to include: PCI, amount of traffic, functional classification, route criticality, and current maintenance (See the budget/prioritization section of this paper). Using the above information, the total maintenance and rehabilitation costs are calculated and long range goals are computed;

g. Report Generator. This section generates customized reports for the user to assist in maintenance decisions;

h. Backup Capabilities: This module backs up the data-base files to protect against data loss and to provide a historical record of allocation and pavement management decisions.

This system is improved in its user-friendly application; however, it is less precise and analytical in the application of most of the modules. The inventory and condition assessment are basically the same as for the NEWMAI system. The improvement in the condition assessment has already been discussed. The scope of work and cost estimate are less precise then the technique used in NEWMAI in that only basic, broad categories of work are identified and assigned an average unit cost. This element is further discussed in the scope of work section of this paper. The deterioration prediction is treated far less scientifically as sections are simply moved from one maintenance category to the next based on preset rules for the PCI rating. The addition of a prioritization element that incorporates a priority index is an improvement. The priority index incorporates: condition assessment, predicted future traffic, type and use of the road, as well as repair cost. PMSC enables the

user to enter budget restrictions and long range goals which the system uses to schedule maintenance and rehabilitation activities. The system is less precise in many areas because it is focused on the network level of decision making. PMSC is not detailed enough for project level decisions, but it does seem to be well equipped for its intended purpose.

4. Integrated Airport Pavement Management System (IAPMS)

The article "Integrated Pavement Management System for Kennedy International Airport," written by Gonzalo Rada, Charles Schwartz, Matthew Witczak and Scott Rabinow (1992) describes a relatively sophisticated network level Pavement Management System. The Integrated Airport Pavement Management System (IAPMS) is a high-level planning tool for the management of large-scale pavement networks. The system was developed only after the Port Authority of New York and New Jersey (PANY/NJ) had undertaken a number of studies aimed at the development of a comprehensive Pavement Management System. From 1980 to 1988, PANY/NJ collected nondestructive deflection and visual condition data and assembled archived data relating to construction history, traffic, soils and materials. The PANY/NJ then performed structural capacity, remaining life, traffic, rehabilitation, and prioritization analyses using the archived data and computer-based analytical techniques. The authors give a detailed description of the IAPMS system's software attributes as well as its elements This system is composed of four major components:

a. Data Base: The data base is established from the inventory element which includes the identification and organization of every segment of pavement and documenting all pertinent information including design, construction, and maintenance history;

b. Analysis and Forecasting: This component includes five essential elements which are integrated to provide a powerful and versatile set of tools for addressing key pavement management issues:

(1) Functional Condition: Consists of the functional evaluation of the pavement using the US Army Corps of Engineer's PCI as in the two previous systems. Predictive equations to describe future functionality are derived from the analysis of the earlier studies by PANY/NJ and information from the Corps' PAVER program;

(2) Structural Condition: Conducts the structural evaluation of the pavements using the California Bearing Ratio (CBR) method for flexible, semirigid and composite pavements; and using the modified Westerguard free slab theory for rigid pavements. Using the current condition and extrapolating from the studies, this element forecasts load carrying capacity, structural remaining life, structural condition factor and time to structural failure;

(3) Traffic Mix Analysis: Determines the loading history of the pavement and converts it to equivalent standard aircraft coverages for a given pavement structural capacity and foundation support value;

(4) Maintenance and Rehabilitation Analysis: Selects the appropriate maintenance and repair activities given the results of the functional and structural conditions, the traffic mix analysis and the current maintenance and repair policies for the PANY/NJ at Kennedy Airport (For a further analysis see the scope of work section of this paper);

(5) Budget Analysis: Uses unit cost data stored in the system data base to calculate the budget forecast for the year, or given prioritization factors and a constrained budget, ranks projects, and selects those which will be performed within a given year (For a more detailed discussion see the budget/prioritization section of this paper);

c. User Interface: An interactive interface provides the user with the capability to query the data base and analyze options and develop forecasts;

d. Display/Report: Data display routines enable the user to view reports and graphics in varied formats from text summaries, map displays, histogram bar charts, pie charts and time functions.

The IAPMS is a more sophisticated system based on local, concentrated research and analysis, but it is also focused at the network level of decision making. The models, information and historic data are specific to airport pavements and work at the Kennedy Airport because they were developed through eight years of extensive on-site testing. The article does not describe the details of the models or calculations used in developing the condition ratings or performance predictions. Three factors of functional rating, structural rating and traffic mix are used to determine the appropriate maintenance strategies and priorities. Only broad general maintenance strategies are identified, however; as the system is designed for network level decisions. The article contains little discussion about how the unit costs for repairs are developed, but most of the maintenance work is done in house. Thus, accurate maintenance repair estimates should have been easy to obtain and are not worth mentioning. The IAPMS includes an improved analysis of loads which can be predicted fairly accurately due to the relatively stable traffic schedule at airports. The report generator for the system improves the budget/priorities element with its capability of producing graphs of different budget options and predicted cost expenditures. The system can also print out graphs of predicted future performance.

5. Bridge Management System (BMS)

Ronald Hudson, Frank Carmichael, Stuart Hudson, Manuel Diaz and Len Moser (1993) develop a more comprehensive approach in applying a decision support system to bridges. In their article, "Microcomputer Bridge Management System," they describe a

bridge management system (BMS) that is designed for small to medium sized states and addresses critical issues such as: incorporating numerous bridge structural types and construction materials; considering network level decisions; employing life-cycle costing models; using prioritization and optimization procedures; and comparing maintenance, rehabilitation, and replacement alternatives through deterioration models. The BMS is a rational and systematic approach to organizing and carrying out all the activities related to managing a network of bridges. The necessary elements required for an effective BMS must incorporate all of the activities listed below:

a. Predicting bridge needs;

b. Defining bridge conditions;

c. Allocating funds for maintenance and improvement actions;

d. Prioritizing bridges for improvement actions;

e. Identifying bridges for posting;

f. Finding cost-effective alternatives for each bridge;

g. Accounting for actual bridge expenditures;

h. Tracking minor maintenance;

i. Inspecting bridges;

j. Maintaining an appropriate data base of information.

The authors divide the system into six separate modules that they use to describe the highlights of the BMS. These modules are a combination of the system's software attributes and its necessary elements. All of the required elements are handled by one or more of the six modules that make up the BMS. These modules include:

a. Data Base: The data base maintains the information necessary for completing all of the system's elements and analysis. The primary data requirements are defined by the

1988 Federal Highway Administration Structural, Inventory and Appraisal data collection procedure. The data base also stores historical data which is used to improve predictions developed in other models;.

b. Level of Service: The user must input level of service goals for each bridge which include establishing attributes such as: vertical clearance, clear deck width, load capacity, and traffic congestion. The values established provide goals that assist in determining the most appropriate repair, rehabilitation and replacement activities for deficient bridges;

c. Improvements: This module identifies bridges that are in poor to marginal condition, recommends cost-effective alternatives and estimates future bridge network performance. Three important elements are completed, including establishing the actual repair, rehabilitation and replacement (RR&R) plan, ranking RR&R alternatives, and preparing an optimization analysis using given budget constraints and level of service goals desired;

d. Maintenance: This module estimates network-wide maintenance needs and accounts for all maintenance costs. Minor maintenance or urgent repair actions that are recorded during inspections are input into the BMS data base. Both the type of action and an importance factor are input through predetermined codes. Maintenance cost estimates are calculated using labor rates that are input into the system. Cost and priority reports can be generated based on the analysis of these user inputs. As maintenance activities are complete actual costs are entered into the system;

e. System Upkeep: The user is able to set the bridge management system parameters and to back up and maintain the data base;

f. Help: A complete on-line help menu is available at all times.

The system is designed primarily to support network level decision making. The principle elements remain primarily the same, but the details are sometimes improved or adjusted to accommodate the peculiarities and differences between managing bridges and pavement. The BMS is unique in the treatment of minor and urgent repair which are evaluated and prioritized separately from the normal repair, rehabilitation and replacement activities. Repair tasks and priorities for minor and urgent repairs are established between the inspector and the network manager without the optimization tools used in the improvement module. The condition assessment is established based on the Federal Sufficiency Rating (FSR) which is similar to the pavement PCI, however, the assessment also incorporates a User-Defined Sufficiency Index (UDSI). The UDSI is based on level of service goals that the user inputs. The condition assessment using the FSR and UDSI is capable of taking into account the actual condition of the bridge, and also evaluating how well the bridge is meeting the needs of the community. BMS also includes an incremental cost-benefit algorithm that optimizes the maintenance activity selection for the scope of work. The details of this algorithm are discussed in the scope of work section of this paper.

6. Rail Management System (RMS)

Donald Uzarki and Sue McNeil (1994) describe a maintenance management system to rail maintenance in the article, "Technologies for Planning Railroad Track Maintenance and Renewal." A survey of a number of large and small railroads found that as of 1984, few railroads use decision support systems and that most of the systems in use are inadequate. An effective system must be able to function at two levels of management detail, network and project. Network level information includes work identification, budget planning, and segment prioritization. Project level management focuses on specific track segments and

identifies the most cost effective repairs. A complete rail maintenance system (RMS) has the following elements:

a. Inventory: Track segments must be identified and pertinent information such as rail weight and curvature must be collected;

b. Condition Assessment: Two guidelines should be used in the assessment:

(1). 1982 Track Safety Standards issued by the Federal Railroad Administration Office of Safety;

(2) Track quality indices (TQI) based on the concept of formulating certain track geometry information into an objective numerical index.

c. Data Analysis: The analysis includes condition prediction, cost estimation, benefit estimation, economic analysis, prioritization and optimization;

d. Reporting features: The capability to produce user customized reports.

The article discusses inspection technologies in great detail. A serious issue facing the railroad industry is the need for quick, precise inventories and inspections. Each rail must be inspected in detail and railroads cannot afford to slow down trains or close sections of track for inspections. While the article identifies the necessary elements, it does not attempt to describe the details of the elements. The article cites recent developments in the automation of track management. These developments are the first steps in accurately modeling expected maintenance activities and costs, and track degradation.

7. Intermodal Surface Transportation Efficiency Act of December 1991 (ISTEA)

Michael Markow (1995) describes the evolution and predicts the future direction of maintenance management systems in the article, "Highway Management Systems: State of the Art." This article provides a quick overview of the evolution of maintenance manage-

ment systems over the last 25 years, concluding that the technological advances of the last few years enable systems to be organized and operated in ways that were difficult to envision as recently as five years ago. The federal Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) dictates the necessary capabilities of a Pavement Management System:

a. Inventory of physical pavement features;

b. History of project dates and types of work performed;

c. Condition surveys including ride quality and categorized pavement surface deficiencies;

d. Traffic Information, including volume, composition and loads;

e. An interconnected database of all related files;

f. Surface condition analysis that identifies the distribution of surface condition throughout the network;

g. Performance analysis that determines current status, and predicts future performance and the remaining service life of each segment;

h. Investment analysis that determines total current and predicted costs at network level, using life-cycle analysis to develop optimal investment strategies at project level;

i. Engineering analysis that provides a technical evaluation of pavement design, construction, rehabilitation and preventive maintenance as they relate to pavement performance.

ISTEA directs that bridge maintenance systems incorporate a rational and systematic procedure for applying network-level analysis and optimization of maintenance for bridge inventories. This includes developing a data base for storing inventory, inspection and cost data and a system of analysis that is capable of:

a. Predicting deterioration of bridge elements;

b. Identifying feasible actions to improve bridge condition, safety and serviceability;

c. Estimating the costs of each corrective action;

d. Estimating expected user cost savings from safety and serviceability improvements;

e. Determining least-cost maintenance, repair and rehabilitation strategies using life-cycle analysis;

f. Performing multi-period optimization;

g. Using feedback from actions taken to update prediction and cost models;

h. Generating necessary summaries and reports.

While providing a lot of general information, the article does not go into specific details about the specific processes required for each element. Because the ISTEA legislation is the result of many significant studies and input from many experts, the requirements dictated in this legislation must be carefully considered when developing any type of Infrastructure Maintenance Management System.

D. Standardizing Element Identification

Figure 2 presents an overview of the six Infrastructure Maintenance Management Systems analyzed and how they relate to the development of the necessary elements required for an effective decision support tool. The titles of the elements are not standard and each system and each article approached the elements from a slightly different point of view. The key note is that while the methods and techniques for applying the elements has steadily grown in sophistication, the principles behind the elements remained the same for

practically every system. The highlighted cells in the table show that the system identified was the first system to incorporate that particular element in the analysis process.

Figure 2   System Element Summary Table

WWDMS 1989	NEWMAI 1991	PMSC 1992	IAPMS 1992	BMS 1993	RMS 1993
Inventory/ Inspection	Improved- Network ID	Improved- Use GIS*	Unchanged	Unchanged	Unchanged
Maintenance History	Not included	Not included	Not included	Not included	Not included
Condition Assessment	Improved- Use PCI*	Improved- Adds severity to PCI*	Improved- Includes structural and functional analysis	Defined by FSR* and user input level of service	Established through Federal guidelines and TQIs*
Not included	Traffic considered in prediction element	Traffic used for priorities not deterioration	**Load Analysis** Specific loads are identified	Not included	Not included
Performance Prediction	Improved- Regression curves	Uses a simplified technique	Improved- Based on site studies	Uses a simplified technique	Included but not described in the article
Scope of Work/Cost Analysis	Improved- Scope based on target PCI*	Uses a simplified technique	Uses a simplified technique	Improved- Uses a cost/ben algorithm	Included but not described in the article
Not included	**Budget Priorities**	Improved- Computes priority index	Improved- Graphs predictions	Unchanged. Based on more user input.	Included but not described in the article

*GIS = Geographic Information System   FSR = Federal Sufficiency Rating
TQI = Track Quality Index   PCI = Pavement Condition Index

III. Recommended Maintenance Management System for Earthen Embankment Dams

A. Decision Level

Most of the literature recommends that the system be designed to assist decision making at both the network and project levels. However, this requirement is rarely met in the current systems being used. Only the smaller systems with relatively few items to manage are capable of developing the details required at project level without being overwhelmed by the voluminous nature of the information required. Most of the current systems are designed to assist network level decisions, sacrificing a level of detail at the project level in order to make the computations for the entire network feasible. In order to keep the magnitude of computations manageable, most of the existing systems categorize the distinct elements of infrastructure, which limits specific project level information. Network level decisions for embankment dams include:

1 Determining budget allocations;

2. Defining maintenance priorities;

3. Establishing inspection frequencies and methodologies;

4. Generating reporting requirements.

Project level decisions require the specific information necessary to determine the optimal maintenance and repair alternatives for each dam. Determining which level of management the EDMS will support is critical to developing an effective system. The relatively few number of dams as compared to segments of roadway and bridges may make it possible to address both levels of decision making, but this issue requires further research.

B. System Environment

Another critical issue in designing an embankment dam management system is developing the balance and relationship between the system's software attributes and its necessary elements. The computer program is built from the software attributes. They provide the foundation and framework within which the elements are performed. The software attributes also provide the vehicle in which information and analysis are passed between the user and the computer. Figure 3 is a representation of the relationship between the system's software attributes and elements.

Figure 3   EDMS Software attributes and Elements
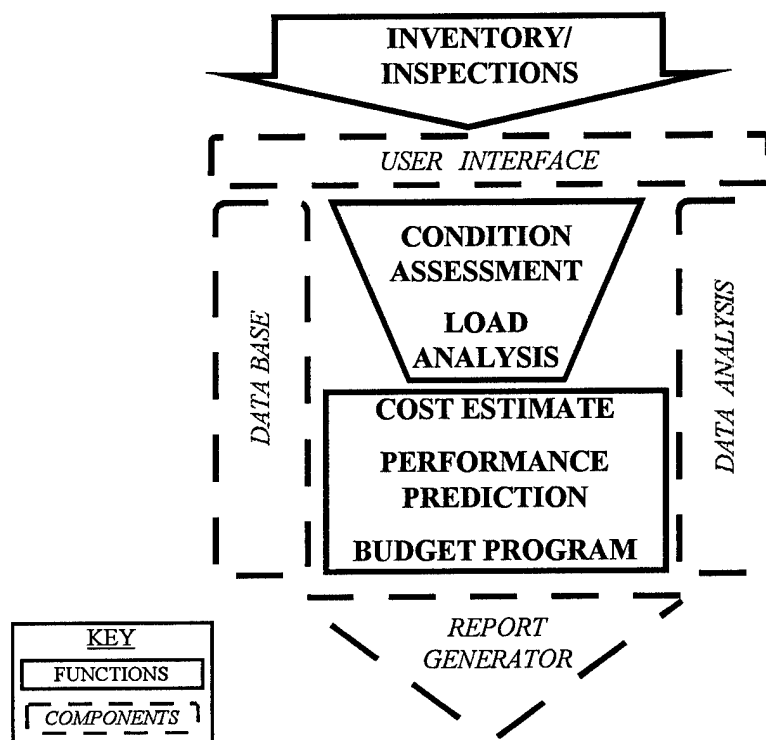
The critical component of data analysis must incorporate the necessary routines to execute each of the elements. The potential for analysis is limited by the physical computational ability of the Identifying and implementing the appropriate type of data base is

equally critical in determining the potential for analysis. In fact, most of the current systems are restricted in some way due to limitations on the data base. The requirements for data input have the potential to ruin an otherwise excellent system because the data entry becomes too overwhelming for the user. Finally, the system's capability for generating meaningful reports and graphs seriously impacts the system's usefulness. The critical point which must be addressed in developing an EDMS is that the necessary system elements cannot be developed without thorough consideration of the entire system and the software attributes they will work within. After a short discussion of the system software attributes, this paper will thoroughly analyze the essential elements necessary to implement an effective EDMS.

1. System Software Attributes

The system must be adaptable and flexible. It must be designed for ease of integration with other systems. Many studies have shown that systems using client-server architecture with integrated data bases have great potential in infrastructure maintenance management. Rada (1990) explains that these systems organize computer resources within networks and locate data and analytic capabilities at the organizational levels at which they are most appropriately used. The basic software attributes of this system should include:

1. User Interface: The system must be user-friendly with an interactive user interface. The user must be able to query the data base for both data review and reporting. A data filtering capability should allow the user to focus on user-defined issues. An on-line, easy to understand help module that can be accessed from anywhere in the program is essential. System upkeep must also be user friendly. The user must have the ability to

backup and edit the database. The user must also be able to easily adjust models and prediction processes as new research and technological advances dictate;

2. Data base: The data base is the repository of essential information for the embankment dam network. The information stored must be adequate to perform all the necessary elements, but it must be minimized to keep from being overwhelming. The system must be able to create multiple working data bases to permit the user to conduct numerous "what if" scenarios without risk of corrupting the master data base;

3. Data Analysis: This module is the heart of the system. The data analysis must perform the relevant computations and output relevant parameters to be used by the other program elements;

4. Report Generator; The results and recommendations must be effectively presented in an easily understandable and clearly visible method. The user must have the ability to custom design forms to meet specific needs as they arise.

2. Essential Elements

Understanding the different elements as they have developed through the evolution of maintenance decision support systems is difficult because of the lack of standards in defining the key elements. The principles behind the elements rarely change from system to system, only the methods of implementation and the categories of description vary from one system to another. The modeling and processes used to complete each element has steadily increased in accuracy and sophistication. The elements will be discussed in more detail in the next section of the paper, but the critical elements for an effective EDMS are:

1. Inventory and Inspection Procedures;

2. Condition Assessment;

3. Load Analysis;

4. Performance Prediction;

5. Scope of Work/Cost Analysis;

6. Budgeting/ Work Prioritization.

IV. Analysis of Critical Elements

To develop a fully functioning and effective embankment dam management system, the six critical elements must all be thoroughly examined and implemented. The elements are all totally interdependent. Each element must be adequately considered and accurately addressed. As one element is developed, the effects it has on the other elements must be carefully analyzed and coordinated. The system's accuracy is constrained by the limitations of the most restricted element. One poorly implemented element totally reduces the validity of the entire system.

A. Inventory and Inspection Procedures

1. Objectives:

Inventory, condition and performance data are the primary sources of information supporting maintenance decisions. This data; however, is most often incomplete, inaccessible or nonexistent. A comprehensive inventory of every component item used in the analysis of the infrastructure system must be entered into the data base. The greatest hurdle that must be overcome in reaching this goal is the problem that inventory data is often in the form of old drawings and files which create a substantial barrier to electronic access (Maser, 1989). Developing a method for compiling operational and maintenance cost histories is additionally critical for establishing a valid system. Accurate performance data and a complete maintenance history of costs and work descriptions significantly improve the accu-

racy of the system's predictions. Operations and Maintenance expenditures cannot be controlled without thoroughly understanding the system's performance and its historic costs.

2. Issues

Retrieving and storing inventory data is a painstaking process that is a major stumbling block for most agencies. The information must be adequate to provide valid recommendations, but retrieving and storing the information cannot be so overwhelming that the system becomes a burden instead of an asset. One of the first decisions that must be made is to determine what information is absolutely necessary for the system to function. The next decision must include establishing how to organize the information. In the article "Developing a Data Base on Infrastructure Needs," Robert Clark and James Goodrich recommend using a relational data base management system. This type of system best handles the required data entry, storage, retrieval and file manipulation required for a decision support system. Using spatial orientation, the data can be oriented into a series of interrelated two-dimensional tables that are easy to construct. This also allows for the expansion of the individual data base tables so that new types of information can be included with existing data. The data base used in the IAPMS system for the Kennedy Airfield is organized in an hierarchically indexed structure on three separate levels. Level I consists of data common to all pavement sections within the network such as maintenance policies and construction costs. Level II consists of basic pavement data unique in each individual pavement sections and Level III consists of field test and survey data and the properties of each individual pavement layer (Rada, 1992).

Developing appropriate inspection methodologies is another crucial issue. The inspections must be designed to first identify defects which require quick remedial action in

order to ensure safe operations. The inspections must also provide the essential information to generate an accurate condition assessment and, at the same time, provide the information required to develop the scope of work and cost for the appropriate maintenance activity. For most infrastructure systems, manual visual data acquisition is proving to be too slow. Research and development efforts are working toward the capability of applying high-speed non-contact sensory techniques. The systems that appear to be in the forefront of developing technology are: optical and infrared image acquisition, storage, and processing; optical character and symbol recognition; ground penetrating radar; and laser metrology (Maser, 1989).

Concurrent with determining the appropriate inspection methodologies, the frequency of inspections must also be carefully analyzed. The issue which must be considered is the frequency of inspections. Increasing the frequency of inspections results in enhancing the quality of information available but also increases inspection costs. Reducing the frequency of inspections lowers costs but the quality information is less timely. Samer Madanat and Moshe Ben-Akiva (1994) address the issue of frequency of inspections in the article, "Optimal Inspection and Repair Policies for Infrastructure Facilities." They modify the Markov Decision Process (MDP). The MDP is one of the most accepted methodologies for mathematically modeling the predicted infrastructure condition between inspections. They develop a methodology called the Latent Markov Decision Process (LMDP) which is used as a systematic methodology for making inspection decisions. This same methodology can be used to account for uncertainty and random errors in the measurement of the infrastructure condition. Hugh Ellis, Mingxiang Jiang and Ross Corotis (1995) develop a different approach to this issue in the article "Inspection, Maintenance, and Repair with Partial Observability." They describe a model for partial observation claiming that no matter what inspec-

tion technique is used, the true state of the infrastructure component is not totally known. Their methodology, Partial Observable Markov Decision Process (POMDP), adds a layer of probability to the discrete state described in the MDP. This approach enables the system to define the optimum inspection policy considering a continuum of states. The POMDP process can be used for the models that assist with the related problems of when to inspect, when to repair and which repair actions should be performed to yield the safest policies at minimum cost.

One of the most critical inspection issues that must be addressed in the future is the lack of consistency among inspectors. Even with the same inspection procedures, inspectors often rely on their own experience to make subjective judgments about specific criteria or they work with different measurement standards during the collection process. These discrepancies may result in an inconsistent and inequitable data base which taints the system's ability to make accurate condition assessments. Automating the process will help alleviate this problem but, as long as people are involved, every effort must be made to minimize the discrepancies in the system.

3. Earthen Embankment Recommendations

The requirement for a complete inventory is essential. Paper inventories and information from the U. S. Army Corps of Engineers' ABS data base must be transferred into the data base to be used as the basis for the EDMS. A further detailed study is required to determine the most effective data base structure for the system. This study should include an interdisciplinary approach to determine the most useable database. Part of the procedure of establishing the EDMS must include specifying the correct inspection procedures. This process must include identifying the necessary information which must be collected to

facilitate development of an accurate condition assessment and to determine the proper scope of work for maintenance and repairs. Currently, the frequency of inspections is dictated by regulations. In the future, this standard should probably be replaced with an optimized inspection schedule produced by the fully functioning EDMS. Determining this optimum inspection schedule by combining cost estimates, condition assessment, deterioration predictions and computer modeling would be a significant contribution to the existing body of knowledge. This new schedule must have sufficiently frequent inspections to ensure deterioration remains controlled but unnecessary inspections should be eliminated.

The data entry process is another issue. Totally automated inspections may not be too far off in the future. The system must be designed to accept this type of information or have the flexibility to be modified to accept inspection data from automated inspections. The decision concerning what information should be entered and stored in the data base is critical. Should the condition assessment be computed from the inspection with only the rating and other specific details entered into the data base, or should all the information from the inspection be entered into the computer which can then compute the condition assessment? Depending on the technique used to determine the scope of work and unit cost of repair, certain specific information will probably have to be captured at the inspection and entered and stored in the data base. All of these factors must be carefully considered in developing the inspection procedures because they will directly affect the other elements of the system. The inspection methodology should describe a data gathering process. This process should be designed so that it can be performed as objectively as possible in order to limit the variance between inspectors. The assessment of the data retrieved will occur during the condition assessment element and should be separate from the actual inspection.

B. Condition Assessment

1. Objectives

The basis for the entire Infrastructure Maintenance Management System is the assessment of the current condition of each item of infrastructure. The purpose of the condition assessment is to accurately describe the current performance of each element of infrastructure so that the individual items can be logically ranked in terms of their performance. For pavements and bridges, performance is extremely difficult to measure. It is a function of the combined effects of loading, environment, age, and past major and routine performance and is reflected by the satisfaction of the user. Performance and deterioration are inversely related. As deterioration increases, performance decreases.

Like performance, deterioration cannot be directly measured, so most PMS and BMS systems measure deterioration by its indicators, specifically, the number of distresses marring the infrastructure which take away from performance. The condition assessment then becomes a measure of the severity and number of distresses that are present. Condition indices have become the excepted means for evaluating condition assessment. By assigning specific numerical values to each type and severity of distress, a condition index provides a logical rating scale to objectively, although indirectly, evaluate performance. Indices for ranking the current assessment have been developed for many of the specific categories of infrastructure. A complete analysis should evaluate both the functional and structural condition together to determine current performance and provide a basis for predicting future performance.

2. Techniques

Bridges are most commonly rated using the Federal Highway Administration's man-

dated Federal Sufficiency Rating (FSR). This rating describes the bridge's ability to serve

its functions relative to the bridges in the network. The FSR is currently used by the gov-

ernment to determine if bridges are eligible for funding under the Federal Highway Bridge

Replacement and Rehabilitation Program. It incorporates bridge attributes such as load ca-

pacity, horizontal clearance, vertical clearance, condition and traffic level (Hudson, 1993).

Most railways use some form of Track Quality Index (TQI) to aid in assessment. The

TQIs are determined by formulating specific track geometry information into an objective

numerical index. They are used to measure the overall track segment condition. Some

TQIs have been modified to include ride quality, derailments, Federal Railroad Administra-

tion safety standards and maintenance standards. The U. S. Army Construction Engineer-

ing Research Laboratory developed a Track Structure Condition Index (TSCI) that is in-

tended for military, short line, and industrial railroads. This index combines separate rat-

ings for rail, joints, fastenings, ties, ballast, subgrade and roadway to develop one overall

index (Uzarski, 1992).

Condition Analysis for pavements is typically performed using the Pavement Condi-

tion Index (PCI) developed by the U.S. Army Corps of Engineers. This method focuses on

the functional condition of the pavement by assigning points for each type of distress that

is currently affecting the pavement. The points are summed to determine a total distress

numerical value that is than subtracted from 100 to give the PCI rating. This method is na-

tionally accepted as an appropriate means for establishing the condition of an existing

pavement and is used or referenced in most PMS systems. However, it falls short of fully

considering the pavement structure or performance. Current research is dedicated to developing more sophisticated approaches to determining pavement condition.

Moshe Ben-Akiva and Dinesh Gopinath (1995) push the process one step further in the article "Modeling Infrastructure Performance and User Costs." The authors develop a two dimensional latent performance model to define the current condition. In this model the condition is defined by both performance and structural condition. These two parameters are indirectly evaluated using distress measurements including: Roughness (RQI); Indexed Cracking (CRX); Rutting (RDMN); Surface Patching (SPAT); Raveling (RAV); and Highway Deflection (DEFS). User costs are also calculated as an additional decision making parameter. User costs are defined as vehicle operating costs and include: fuel consumption, tire wear, maintenance parts, maintenance labor and lubricant oil consumption. All three critical parameters must be considered in evaluating the condition because they affect the maintenance and rehabilitation decision making. Structural integrity must be considered when evaluating maintenance versus rehabilitation decisions. User costs are critical in identifying the optimal maintenance strategies.

The State Increment Method of Life-Cycle Cost Analysis (SILCCA) works on a different method of condition assessment. Presented in the article, "State Increment Method of Life-Cycle Cost Analysis for Highway Management," (Ravirala, 1995) this system assists in project-level evaluations of highway infrastructure maintenance options. The system was developed by the New York State Thruway Authority (NYSTA) and Rensselaer Polytechnic Institute (RPI) as a Pavement Management System for the preservation and restoration of the Thruway's highway infrastructure. This method is designed around the use of current depreciation models which define the pavement as it transforms from one distinct state to

another. The condition assessment for this system rates each pavement section by the "state" in which it should fall. The "states" are defined by six variables:

    a. Pavement Type - either concrete or overlaid;

    b. Equivalent single-axle Loads (ESAL) per year - four categories ranging from less than 3 million to greater than 8 million;

    c. Life Cycle Phase - four phases based on age and maintenance activities performed;

    d. International Roughness Index (IRI) - describes pavement ride quality and is broken down into three categories: Excellent, Good or Fair based on numerical results;

    e. Slab/Surface Rating (SSR) - summarizes the distress condition and is rated as Excellent, Good or Fair based on numerical results;

    f. Joint/Crack Rating (JCR) - separated into the same three categories and is used to define the distress condition.

This method establishes an accurate and detailed condition characterization and provides an effective analytical process as well as the efficient computational capabilities necessary to manage the large number of roads in the NYSTA system. Using this system, deterioration can be predicted for segments as they move from state to state and specific maintenance activities can be identified to optimally control the transformation from state to state. The state-increment method can be used at the project level to select the minimal cost design alternative by considering both agency and user costs and performing a life-cycle analysis for each segment. The system is capable of predicting the effect of treatments on pavement condition and remaining life which aid in determining the optimal time and condition for resurfacing and rehabilitation.

Angela Weissmann, Frank McCullough and Ronald Hudson (1994) describe another condition assessment model in the article, "Reliability Assessment of Continuously Reinforced Concrete Pavements." Their Continuously Reinforced Concrete Pavement (CRCP) model was developed using the Texas Department of Transportation data base and is designed specifically for Texas roads and maintenance policies. The authors argue that the traditional definitions of structural and functional pavement failure do not work because pavement sections are not permitted to reach the point of functional failure or structural collapse. The model uses three distress manifestations that have been found to be good indicators of CRCP performance. The distress index, termed Z-index, was developed using condition surveys and is designed to accurately capture the characteristics of the Texas CRCP deterioration. The Z-index gives pavement ratings between zero and one, with a perfect pavement having a score of one and a score of zero describing a pavement that is a candidate for rehabilitation. The index is derived from the three critical indicators: minor punchouts, severe punchouts and number of patches. Each of the indicators is measured in number of distresses per kilometer of highway. The change in the Z-index from one inspection to the next is plotted against a Weibull distribution that represents Equivalent Single Axle Loads (ESAL). From this plot, the probability of failure can be determined for each section. The sections with the highest probability of failure need the most immediate maintenance attention.

3. Earthen Embankment Recommendations

L. Chourinard, G. Andersen and V. Torrey III (1996) describe the condition assessment process that will be used for embankment dams in the article, "Ranking Models for Condition Assessment of Civil Infrastructure Systems." This method is unique in that it is focused on performance directly, i.e. each component is rated based on its ability to per-

form specific functions. The strategy incorporates the total systems approach and uses interaction matrices to identify important components and to describe the nature of interactions between components. This function-based condition indexing system rates each component of the embankment dam in terms of its ability to perform specific functions. These functions are identified in the repair, evaluation, maintenance or rehabilitation (REMR) objectives established by the U.S. Army Corps of Engineers. The condition assessment is based on a strategy in which each functional system is identified and the individual components are weighted by their relative importance to the dam's overall performance. The overall condition of each embankment dam is determined by weighting the effect of each deficient component relative to the embankment dam's ability to perform its assigned functions.

One last point for the consideration of condition assessment as applied to embankment dams is that even with relatively simple systems like pavements, different evaluation schemes have been developed to accommodate for differences in local maintenance policies and construction materials. As the EDMS evolves for dams, it will probably also need modifications, especially to meet the potentially diverse needs of the U. S. Corps of Engineers, Hydro Quebec and private dam owners.

C. Load Analysis

1. Objectives

An accurate load analysis must be completed to assist in assessing performance and determining the deterioration rate of the element of infrastructure. This analysis is a level of sophistication that is not incorporated in to most management systems. Deteriora-

tion occurs through two mechanisms environmental and interactive. Interactive deterioration is the spread of existing deterioration and the effect it has on local areas. Environmental deterioration develops from external forces and the environment in which the infrastructure is located. (Mishalani, 1995) The load analysis must include identifying the critical causes of deterioration, determining their intensity and identifying how they impact the predicted deterioration curves. If the environmental causes of deterioration vary significantly according to the climate or region, then loading must be considered in order to accurately predict deterioration for each specific item of infrastructure. Evaluating the future loading on the infrastructure does not necessarily have to be addressed as a separate element, but it must be considered and accounted for in the deterioration model.

2. Issues

For pavements and bridges, the most critical load affecting deterioration is the level of traffic. The NEWMAI system considers loading in its deterioration prediction, but it does not include the load analysis as a separate element. The system incorporates a "vehicle load factor" and a "durability factor" in its distress prediction equation. The vehicle load factor (ESAL), defined by historic traffic quantities converted to millions of equivalent 18 kip single-axle-load repetitions, is used to predict the change in density of the distress. The equation is based on the original type and severity of distress, the estimated CBR for the section's subgrade and the vehicle load factor. This factor is based on historic traffic levels and assumes traffic will remain constant over time; however, the program has the capability to adjust the factor if traffic is predicted to change significantly. The article does not describe what method is used for determining the historic level of traffic. The durability factor accounts for the interactive deterioration and is calculated based on the severity of the distress and the length of time since construction or the last repair (Berger, 1991).

The IAPMS at Kennedy Airport includes the load analysis as a separate element. Using established references and calculations, the system converts a mix of aircraft types to equivalent standard aircraft coverages for a given pavement structural capacity and foundation support value. The IAPMS stores approximately 120 different aircraft and their respective gear-load characteristics in the data base for use in the traffic mix analysis. The loading is used to assist in calculating structural remaining life and to determine the optimum maintenance strategy (Rada, 1992).

3. Earthen Embankment Recommendations

While traffic loading does not apply to embankment dams, the effects of the weather and the environment must be considered in determining the predicted rate of deterioration. Embankment dams with similar construction and experiencing similar distresses will deteriorate at different rates based on the climate and environment. Freeze/thaw cycles, draughts, amounts of precipitation, local vegetation, vandalism and wave action all substantially affect the deterioration rate of an embankment dam. Since all of these factors vary significantly from region to region, the deterioration model must incorporate the most critical factors in its analysis. It is beyond the scope of this paper to determine all of the relevant factors and their effect on embankment dam deterioration.

The essential point which must be made is that these factors must be considered and incorporated as part of the deterioration model. These factors will also be extremely crucial in determining the optimum maintenance strategy for the embankment dam. Each maintenance activity must be considered for its usefulness in reducing the effects of the major causes of deterioration. It is very likely that a maintenance activity that is effective in the warm, moist climate of Louisiana may not be as effective in the hot and dry climate of

Arizona or the deep cold of Ontario. This issue will be much more critical for embankment dams, as the maintenance activities for pavements seem to vary little from climate to climate.

D. Performance/Deterioration Prediction

1. Objectives

One of the most critical and beneficial elements of an Infrastructure Maintenance Management System is its capability to accurately predict the future performance of each element of the infrastructure. For pavements and bridges, performance is measured in terms of deterioration and its indicators, because performance is too difficult to measure and quantify. For pavements and bridges, the effects of deterioration must be monitored and controlled or they can be devastating. Rehabilitation costs significantly increase as the infrastructure deteriorates. Effective and routine maintenance will significantly reduce maintenance costs as long as the maintenance activities are effectively timed. The difficulties arise in determining the current deterioration and in developing an accurate enough forecast of deterioration that the optimal maintenance plan can be developed. As stated before, deterioration is difficult to measure. It is an unobservable entity whose manifestation results in observable surface and subsurface distresses (Ben-Akiva, 1993). Only the indicators of deterioration are measurable, so a deterioration prediction model must be designed around the limits of the indicators. To be effective, the model must be accurate enough to determine both the optimal timing and methods for routine maintenance activities, and the optimal type and timing of rehabilitation or reconstruction activities.

2. Techniques

Performance/deterioration is most often quantified by condition indexes that are developed using discrete ratings to qualify the current condition. The discrete ratings are used instead of continuous condition indices primarily for reducing the computational complexity of the maintenance and repair decision-making process. Two statistical approaches to model deterioration are:

a. Construct an acceptable model of the failure mechanism and incorporate the variability of each design factor into the model;

b, Directly derive a model of deterioration from performance observations.

The first approach is best when the nature of the failure mechanism and the variability of the components is known or can be accurately identified. This approach hardly applies to deterioration, so the second approach is most often used. The second approach is most applicable when neither the nature of the failure mechanism nor the variability of the design factors are easily obtainable (Weissmann, 1994). Deterioration models are typically incremental models that predict the changes in condition based on observations over time. "Incremental models are more realistic representations of the deterioration process than models which predict condition directly because condition at a point in time is a function of both condition at a previous point in time and other explanatory variables such as age, traffic, weather, and maintenance" (Madanat, 1995). Markovian transition models have been used extensively in prediction models for Infrastructure Maintenance Management Systems. These models are based on transition probabilities that specify the likelihood that the condition of an infrastructure facility will change from one state to another in a specified unit of time. This specified unit of time is typically determined by the time between inspections.

There are three general modeling approaches for the state description: an individual item model, a counting process and a classification scheme (Scherer, 1994). For most systems, the individual model is not possible because of the resulting number of individual states. Commonly used MDP solution techniques require consideration of all possible states. For a system with a large number of infrastructure items, the number of states quickly become "computationally intractable for any existing computer" (Scherer, 1994). The counting process identifies the number of individual infrastructure items within each state. This process maintains the same decision-making information but it results in a loss of individuality of each item of infrastructure. The counting process substantially reduces the total number of states but, for very large infrastructure systems, even these numbers are too large. For these large systems, a combination of hierarchical breakdowns into specific classifications and the counting process is needed in order to generate a deterioration model that is computationally feasible. This model would work at the network level and generate a policy for each classification set, but not for each bridge. This model may result in loss of decision-making information if it is not integrated with a project level model for the individual items of infrastructure. Most current systems utilize the Markovian transition models that group the items of infrastructure into categories with common attributes as they apply to the infrastructure's deterioration.

The Markovian Decision Process (MDP) is based on the property that, "the condition distribution of a transition from the present state to any future state, given the past state, is independent of any past states and depends only on the present state" (Madanat, 1994). MDP is designed to model discrete states. Using this process, transition probabilities are developed to link current states to future states. A one-step transition matrix is generated for each state to predict the future state. Future states for several years into the future can

be predicted by Markov chains that are formed by multiplying the transition matrices to-
gether. These transition probability matrices are established based on professional experi-
ence/judgment and linear regression or other models developed from existing historic data
bases.

An example transition matrix consisting of 9 possible states is depicted in Figure 4.
For this case, 9 is the highest state of newly constructed/renovated and 3 is the lowest state
requiring immediate rehabilitation. The row identifies the current state of the item of infra-
structure, the columns identify the possible deterioration states, and the cells identify the
probability of transitioning to the future state.

Figure 4   Example Transition Matrix (Scherer, 1994)

Future Present	3 Worst	4	5	6	7	8	9 Best
3	1	0	0	0	0	0	0
4	0.234	0.767	0	0	0	0	0
5	0.067	0.167	0.767	0	0	0	0
6	0	0.087	0.130	0.783	0	0	0
7	0.003	0.021	0.102	0.332	0.542	0	0
8	0	0.004	0.021	0.103	0.334	0.538	0
9	0	0	0	0	0.167	0.583	0.250

As an example, an infrastructure item with a rating of 6 has a 0.087 probability of deteriorating to a 4, a 0.13 probability of deteriorating to a 5, and a 0.783 probability of remaining at 6 for the next year.

Poisson mass functions and distributions have been found to not only accurately model the deterioration of bridge condition states, but also to agree with the bridge engineering intuition of Virginia Transportation Research Council (VTRC) experts (Scherer, 1994). In the article, "Poisson Regression Models of Infrastructure Transition Probabilities," Samer Madanat and Wan Hashim Wan Ibrahim (1995) continue the use of Poisson regression models. The authors found that the Poisson regression model has major advantages over the commonly used linear regression approach. It allows the program to explicitly link deterioration to relevant explanatory variables and eliminates the need to artificially segment the sample as is the case with the linear regression method. Also, since the entire data set can be used in the estimation process, a full transition matrix can be estimated and better statistical results can be achieved. The Poisson regression explicitly recognizes the discrete nature of the current state unlike linear regression. Presently only discrete models have been developed for predicting future performance. Because of the reliance on the MDP, continuous models have not been developed.

The source data for the study was the 5,700 state-owned bridges included in the Indiana State Bridge Inventory data base. The study added a negative binomial model as an extension of the Poisson model. The negative binomial model relaxes the assumption of equality between the mean and variance of the dependent variable, which was the case for the Indiana data set. The dependent variable in the study was the number of drops in condition state in one inspection period. Some of the empirical results of the study include:

a. The extent of chloride content is the major indicator of deterioration for new bridge decks. For moderate and extensive deterioration, the extent of spalls and delamination is the primary indicator of deterioration;

b. Within the state, bridge decks in the northern region deteriorate faster than decks in the southern region due to the effects of de-icing salts;

c. Bridge decks on older bridges have a higher rate of deterioration than decks on new bridges;

d. The incremental average daily traffic affects the deterioration rate of bridge decks. The deterioration rate of bridge decks on secondary roads increases with traffic;

e. As bridges increase in the number of spans, deterioration increases;

f. Simple concrete bridge decks deteriorate faster than other types of bridge-deck structures;

g. Bridge decks on interstate highways deteriorate slower than primary highways, which deteriorate slower than bridge decks on secondary highways;

h. Wearing surfaces with protective systems deteriorate slower than bridge decks without protective systems.

In the article, "Probabilistic Behavior of Pavements," Kelvin Wang, Jon Zaniewski, and George Way (1994) describe their latest advancement in the prediction methodology for Markov-based Transition-Probability Matrices (TPMs). The authors recommend using the concept of pavement probabilistic behavior curves (PBC) modified with accessibility rules as the best method for predicting pavement performance. These pavement probabilistic curves were developed in conjunction with the Arizona Department of Transportation (ADOT) and their award winning Network Optimization System (NOS). NOS, developed in 1980, was the first successful implementation of sophisticated mathematical models based

on large scale optimization and stochastic prediction techniques for pavement management. The system was updated in 1992 with improved model structure and performance prediction using probabilistic behavior curves. The NOS system uses Chapman-Kolmogorov equations to provide a method for computing the sequential transition probability matrices. These matrices are used to calculate the expected serviceability-age/traffic relationship over the entire design period and to demonstrate pavement long-term behavior. The Chapman-Kolmogorov equations are an aggregate prediction method based on statistical assumptions which replace the technique of matrix multiplication to derive sequential TPMs.

The NOS system uses 15 road categories to classify the highway system in Arizona. The categories are based on traffic, region and functional class. In addition, the system works on 45 possible condition states which are defined by the degree of roughness, level of cracking, and index to first crack. Each pavement section is assigned to one of the 15 road categories and placed into one of the 45 possible condition states based on inspection results. The NOS system considers five maintenance strategies for rehabilitation actions which range from routine maintenance to applying different types and thicknesses of asphalt and concrete courses. Reviewing the historical data from the ADOT pavement management data base, the authors developed accessibility rules to govern specific state transitions and TPMs for all 15 road categories. The TPMs were used to conduct the analysis of long-term probabilistic behavior for the entire design period during which one rehabilitation is applied. The data generated from the analysis is used to plot pavement Probabilistic Behavior Curves (PBC) which define the probability of being in a given condition state over time. It is important to note that the ADOT pavement management data base had sufficient historical information to permit direct determination of transition probability matrices (TPMs)

only after the original system had been operating for 13 years. The PBCs and the new TPMs are shown to accurately predict pavement performance.

This new modeling system is credited with significantly improving the NOS system's reliability and efficiency. Some of the revelations from the historical data review included observing that poor pavements did not transition to good condition under routine mainte-nance. Low level routine maintenance applications such as crack sealing and patching im-proved pavement condition only for a short period of time. Deficiencies re-occurred or new deficiencies appeared in a time frame ranging from a few months to a year. Low level rou-tine maintenance results in a slight improvement in roughness, but it will not improve the condition state to a new state. They also found that pavement condition does not deterio-rate more than one level in one year.

The Markov Decision Process is improved on in the article, "Infrastructure Manage-ment Under Uncertainty: Latent Performance Approach" (Ben-Akiva, 1995). In this article, the authors argue that substantial uncertainty exists in predicting performance. Uncertainty is introduced in the measurements implemented to describe current performance and in the calculations and models created to predict performance. The Latent Markov Decision Proc-ess (LMDP) is used to account for uncertainty. This method is an extension of the tradi-tional Markov decision process (MDP), but it incorporates the probabilistic relationship that exists between deterioration measurements and predictions, and true performance. A measurement error model is included that establishes a relationship between the measured condition indicator and the true condition. The model incorporates both systematic biases and random error. A factor analytic approach was used to obtain unbiased estimates of the uncertainty parameters. These parameters were determined using the covariances be-

tween multiple measurements of the same distress by different technologies. The performance prediction is developed through a deterioration model and a measurement model that incorporate explanatory variables, maintenance actions and condition indicators. The authors claim that this model is superior because most existing deterioration models are estimated with data from in-service pavements. These pavements are maintained by highway agencies in response to their level of traffic. As a result, pavements with the highest usage receive the highest level of maintenance. If the models do not take into account these two competing mechanisms of deterioration and maintenance then the model will be skewed and inaccurate.

Rabi Mishalani and Haris Koutsopoulus (1995) further develop the method for predicting infrastructure deterioration in the article, "Uniform Infrastructure Fields: Definition and Identification." This improved method is specifically designed for infrastructure facilities such as highways and railways. The authors demonstrate that using detailed spatial distress data is critical for accurate deterioration predictions. They explain that pavement is currently aggregated into distinct identifiable sections for inventory and analysis using casual variables such as daily traffic volume and mix, structural design, quality of construction, environmental factors and maintenance history. They argue that the analysis must first identify the boundaries of homogeneous fields by considering the types and severity of distresses present in the pavement. Once these uniform fields have been identified, the deterioration for each field can be more accurately predicted. This process is designed to span the gap in scale between the recently available microscopic detailed distress data and the macroscopic nature of the decision making process.

This uniform field method takes into account two deterioration mechanisms: environmental and interactive. The environmental mechanism describes deterioration as a consequence of design, traffic, and the surrounding environment. The interactive mechanism describes deterioration as a result of distress at one location influencing the deterioration of neighboring locations. The pavement must be divided into uniform fields that will react similarly to environmental and interactive distresses, otherwise predictions for the deterioration of pavement sections become distorted and inaccurate as they cross over these natural boundaries. The article demonstrates a method for identifying the fields using a stochastic process and a spatial model which, while it still has problems, is much more accurate in capturing both the macroscopic and microscopic scale of deterioration behavior.

3. Earthen Embankment Recommendations

Crucial to the viability of the system is its ability to accurately predict future performance. Bridge and Pavement Management Systems have been able to predict performance by modeling its inverse, deterioration. Years of study and data collection have resulted in relatively accurate models based on the Markov Decision Process and variations of the MDP. The literature on infrastructure management does not include information on performance predictions for embankment dams. However, the principles and methodologies that have been developed can most likely be modified to account for embankment dam deterioration. A few critical points must be addressed:

a. Pavement managers work with deterioration because they cannot measure performance. Performance is difficult to describe when the user is the general public. The general public is an entity more diverse than the pavements and bridges that make up the road system itself. Embankment dams have a different purpose and embankment dam

performance may be easier to quantify and measure. It may be simpler to measure performance, especially against the REMR objectives, rather than try to quantify deterioration.

b. The majority of the Pavement Management System is driven by the capabilities and limitations of the deterioration model. Most systems are limited by the deterioration model because of its vast computing requirements. Using the Markov Decision Process or one of its variations requires that specific states of deterioration be established and analyzed. This process evaluates each state based on every possible state of existence. This means that a management system will soon become computationally intractable if the system has a large number of specific infrastructure items or if it incorporates a large number of possible states for each item. The majority of Pavement Management Systems use the category method discussed above because it greatly reduces the number of necessary computations and it also eases the requirement for modeling information. Instead of being required to track each type of distress through the progress of deterioration, only the changes from one state to another must be recorded. If the category method is used than the information to make precise, accurate scope of work and cost estimations for future maintenance may be lost. The category method then drives the way the current condition assessment should be determined and it determines the information available to make future predictions.

c. If the Markov Decision Process is used in conjunction with the category method for analyzing deterioration then careful thought and consideration must go into establishing the appropriate categories. The categories must be established such that every dam in the category will deteriorate in the same manner. Once again, it might be easier to look at performance when defining the categories. The categories should be meaningful and should be limited to as few as possible. They must have meaning to both the condition assessment and the determination of scope of work and maintenance costs. If the specific num-

ber of embankment dams is small enough that tracking them individually is possible, then the number, type and severity of distresses will have to be grouped in categories so that they can be modeled using the MDP process. The entire management system must be viewed as interrelated elements, and if the prediction model requires that the condition be established in a limited number of distinct states, then the initial condition assessment and the maintenance cost estimate must be developed around those states.

d. The most critical process in developing an accurate deterioration model is the process of collecting meaningful, accurate data. The biggest complaint in developing most of the systems was that plenty of data was available, but the data was not in the correct form or, for some other reason, was unusable. The first systems developed models based on experience and judgment and only after these systems had been around a while was enough appropriate data collected to develop accurate models. The use of states for the Markov Decision Process also simplified the collection process. Once the states were defined, the specific parameters could be identified, measured and tracked. The process of collecting appropriate data took 10 to 15 years for most systems and the research and analysis is still going on. The IAPMS at Kennedy Airport had the opportunity to design and conduct its own tests, and that process still took eight years. Even as the process of developing the system is underway, the managers in the field must be told what information is critical to collect.

e. The historic data is necessary for developing the correct deterioration model that is necessary for the MDP. Within the literature, experts had different opinions of what models best predict the deterioration. Several curves were suggested and used in different systems: linear regression, Poisson distributions, logarithmic curves and survival curves have all been used. The best model is probably specific to each type of infrastructure, but

the only way to determine the best model is to have a complete and accurate historic data base against which to test the model.

     f. Predicting future performance is the lynch pin that combines all the elements. This element will drive the methodology for the rest of the system. The best possible prediction model must be developed initially with the historic information that is now available. The system should be designed with the flexibility to adapt to new prediction models as they are developed and it should record information over time to continuously update and improve its own estimates.

E. Scope of Work/ Cost Estimation

1. Objectives

     Based on the current and predicted levels of deterioration and the executed load analysis, the system must first determine the scope of work that most adequately satisfies the competing requirements of limited budgets and providing best quality service. Life cycle cost analysis is essential in determining the optimal repair strategy. Once the best repair strategy is determined and the scope of work identified, the system must be able to compute the current and future costs of conducting the work. The typical attitude for determining construction repair costs is reflected in the statement, "Due to the general absence of detailed cost and unit quantity data, a consultant was hired to obtain budget information on current operation and repair costs. These costs were derived by interviewing numerous public and private facility managers and reviewing cost references and published maintenance manuals" (Thornton, 1993).

2. Techniques

### a. New Maintenance Computerized System (NEWMAI)

The NEWMAI Pavement Management System focuses on the project level of deci-

sion making. It incorporates the most sophisticated maintenance selection procedures.

The system includes twelve distinct maintenance actions which are appropriate for the

nineteen possible distress types that can be identified within the system. The optimal repair

response for each type and severity of distress present is selected based on expert opinion

and judgment. This selection is preset in the data base. The optimal repair responses can

easily be adjusted by the user according to local experience. The possible repair responses

are:

1. Do nothing	7. Pothole filling
2. Crack sealing	8. Heat and sand
3. Joint sealing	9. Seal coat/fog seal
4. Skin patching	10. Surface treatment
5. Partial patching	11. AC overlay
6. Full-depth patching	12. Shoulder filling

The unit cost for each activity was determined based on an earlier study. These

costs do not get adjusted for the time or location of construction. The priority of mainte-

nance activities is determined first, according to the severity of the distress, and secondly,

by the type of distress. A target Pavement Condition Index (PCI) curve is established for

each segment of the pavement based on the predicted PCI and the years remaining until

the programmed rehabilitation of the road is scheduled to occur (See Figure 5).

The goal is to maintain at least a minimal standard PCI rating for the pavement be-

tween major rehabilitation activities. Maintenance activities are then evaluated by their po-

tential to reach the target PCI. The most severe distresses are corrected until the PCI goes

above the target PCI. As long as the PCI remains above the target PCI, no repair work is

done.

Figure 5   Target PCI for Maintenance Activities (Berger, 1991)
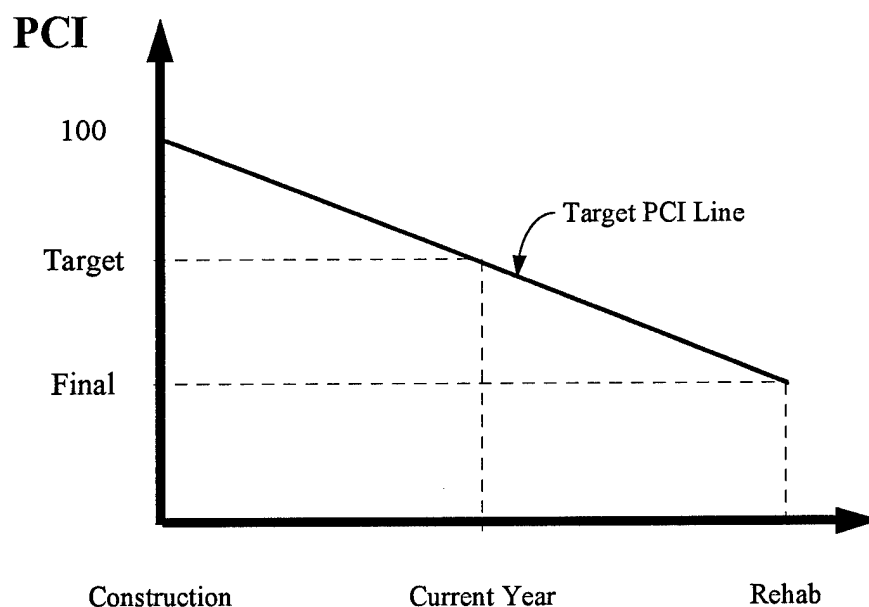
NEWMAI also predicts the effectiveness of the maintenance activities on different

types of distress. The system includes a subroutine that allows for a percentage of the dis-

tress to reappear each year after the repair is complete. The percentage of reappearance

depends on the original severity of the distress and the repair strategy employed to correct

the deficiency. These effectiveness ratings were determined based on the writer's experi-

ence and judgment. The program also determines the additional vehicle operating costs,

based on the deteriorating PCI, to aid in the cost/benefit analysis. The system can calcu-

late and predict maintenance repair costs for each segment of pavement or for the entire network (Berger, 1991).

b.   Pavement Management System for Small Communities (PMSC)

The small communities Pavement Management System, PMSC, limits repair strategies to the six general categories designated by U.S. Department of Transportation (DOT) guidance:

1. Do Nothing	d. Deferred Action
2. Routine Maintenance	e. Reconstruction
3. Preventive Maintenance	f. Rehabilitation

The DOT guidance also lists the various repair techniques that apply to each maintenance category based on the type of existing pavement. The optimal repair strategy is determined based on the PCI and the age of the pavement with little consideration of performance or costs (See Figure 6). The user does have the option to review and modify the selection. The costs associated with the six strategies are, "input by pavement management professionals who maintain current cost data on maintenance and construction of road surfaces" (Tavakoli, 1992).

Figure 6   Maintenance and Rehabilitation Strategies (Tavakoli, 1992)
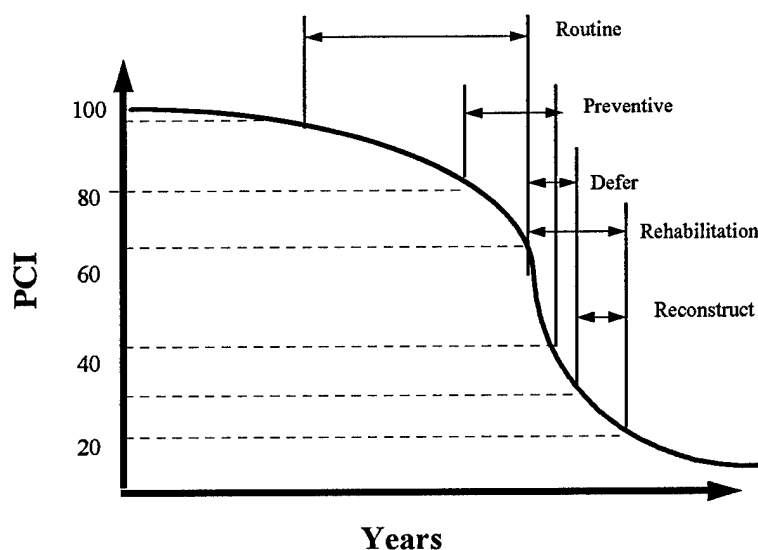
c.   Integrated Airport Pavement Management (IAPMS)

Kennedy Airport's IAPMS is focused on assisting decisions at higher levels of maintenance management. The system addresses only three possible maintenance activities.

1. No action

2. Place seal coat

3. Construct asphalt concrete overlay

The PANY/NJ maintenance and repair policies are incorporated into the system and used to determine the optimal maintenance response. The strategy is chosen based on pavement rank, pavement condition index and structural remaining life. The article mentions that construction costs are entered into the data base, but it does not address how the costs were developed or if they are adjusted over time. Given that the airport has all its pavement in a concentrated area and that all the construction and repair is done locally, the

costs probably remain relatively constant and the data base can be easily updated if any

major changes in cost occur (Rada, 1992).

d. Bridge Management System (BMS)

The BMS presented in the article "Microcomputer Bridge Management System," is

designed to evaluate, at most, seven different maintenance responses for each bridge in

the network including:

1. Major maintenance,

2. Rehabilitation of structure only,

3. Full bridge rehabilitation,

4. Replacement of bridge,

5. Replacement of deck only,

6. Widening and full bridge rehabilitation,

7. Widening only.

The system implements a unique optimization process in selecting the proper scope

of work. The user is given the opportunity to input essential data for the maintenance deci-

sion including entering estimates for maintenance costs, condition deterioration predictions

and user costs. If the user does not enter values, then the system uses calculated or de-

fault values in the data base for these estimates. Using this information, the system then

performs an incremental benefit cost optimization procedure which works on The Incre-

mental Benefit-Cost (INCBEN) Algorithm. The cost-benefit ratio is calculated for each

maintenance alternative on every bridge that is considered deficient by the condition as-

sessment. As shown in Figure 7, C1 represents the costs for routine maintenance and B1

represents the benefits of routine maintenance. C2 and B2 represent the costs and bene-

fits of the next level of maintenance, which is rehabilitation of structure only. The ratios for

the activities are:

1. Routine Maintenance: B1 / C1

2. Rehabilitation of Structure: (B2 - B1) / (C2 - C1)

The analysis continues for all seven activities and the activity with the highest ratio is

chosen. The minimum acceptable benefit-to-cost ratio is one. Other than explaining that

the benefits and costs are calculated using Equivalent Uniform Annual Cost (EUAC)

method, the article does not state how all the costs and benefits are determined. The sys-

tem also has the capability of considering budget constraints in the analysis to determine

the possible option with highest cost-benefit ratio. This option within the budget constraint

with the highest ratio is selected as the optimal solution (Hudson, 1993).

Figure 7   Comparing Alternatives using Incremental Benefit/Cost Ratio (Hudson, 1993)
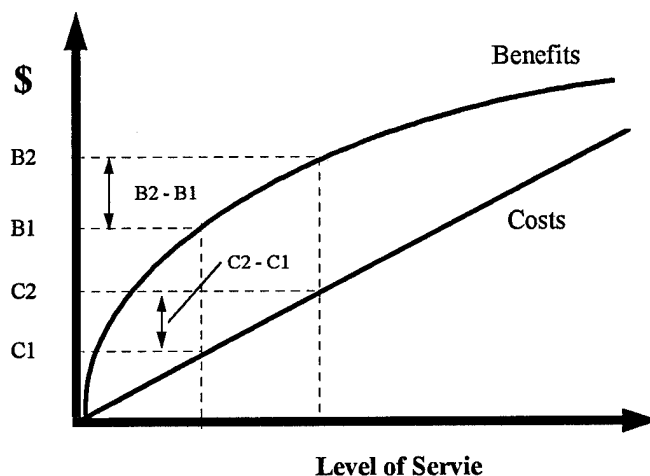
3. Maintenance Effectiveness

Relatively few articles have been written that attempt to quantify the effectiveness of pavement maintenance. Two articles recently published report very similar findings. The first article, "Effects of Pavement Age and Traffic on Maintenance Effectiveness," (Al-Suleiman, 1991) divided pavement age into three groups:

Group 1: Pavements in excellent or very good condition, ranging in age from newly constructed or renovated to five years old;

Group 2: Pavements in fair to good condition ranging in age from five to fifteen years after major improvement or reconstruction;

Group 3: Pavements in poor condition with ages of 10 years or more.

The study found that the timing of preventive maintenance is critical. The effectiveness of routine maintenance can be expected to be the highest for pavements in Group 2. Routine maintenance for pavements in Group 1 often results in increased pavement roughness, and pavements in Group 3 have a greater need for rehabilitation or reconstruction then preventive maintenance. Six routine maintenance activities were considered during the study: shallow patching, deep patching, premix leveling, seal coating, sealing longitudinal cracks/joints and sealing cracks. These activities were broken into three maintenance categories based on increasing levels of expenditure on maintenance levels. The categories include:

a. Shallow and deep patching;

b. Patching and joint/crack sealing;

c. All patching and sealing. Including any of a number of combinations of the six maintenance activities with either premix leveling or seal coating involved.

Maintenance work involving the premix leveling and seal coating was found to provide a relatively higher effectiveness than work involving only patching and joint/crack sealing. The study also verified that higher levels of equivalent single axle loads (ESAL) result in higher increases in the change of roughness.

A second study was described in the article, "Effects of Routine Maintenance on Flexible Pavement Condition," (Al-Mansour, 1994). This study analyzed the effects of pavement age, traffic load, climate, initial design/construction and maintenance on pavement performance using regression analysis. Six maintenance categories were considered for this study:

    a. No maintenance;

    b. Basic Routine Maintenance (BRM) - includes patching and crack sealing

    c. BRM and chip sealing;

    d. BRM and sand sealing;

    e. BRM and premix leveling;

    f. Basic shoulder maintenance activities.

The study developed models for predicting the change in pavement roughness measurements based on the factors listed above. Applying the model, the researchers were able to make several conclusions:

    a. Maintenance effectiveness increased as pavement aged until the pavement roughness neared a "terminal value" indicating resurfacing is required;

    b. The average reduction pavement roughness due to maintenance ranged from 1% to 55%, depending on the type of maintenance and the pavement roughness at the time of maintenance action;

c. Shoulder maintenance does not directly affect pavement roughness, however it can reduce deterioration of the pavement surface resulting from improper drainage and seepage of moisture to its subbase;

d. Basic routine maintenance and sand sealing were more effective on pavements in good condition than basic routine maintenance and chip sealing, but less effective when applied to pavements in fair or poor condition.

These two studies are important in developing the foundation for creating a process of determining an effective scope of work based on the condition assessment for pavements. While the results do not directly apply to the development of scope of work for embankment dams maintenance management systems, the study does, at a minimum, identify some of the factors which should be considered when analyzing the optimum scope of work for embankment dam maintenance. A significant contribution to the development of an EDMS would include using historic databases to analyze the effects of differing maintenance activities on the condition rating developed by Andersen (1996).

4. Earthen Embankment Recommendations

None of the systems truly attacks the development of the unit cost for repair in a scholarly manner. Using unit costs, the systems adjust the cost for the scope of the project, but these costs are not adjusted for time or location. The costs are either developed from past studies or, for more accuracy, the user can input current costs. The scope of work is always generated from the initial inspection. The type of distress to be repaired, the severity of the distress, and amount of area impacted are all derived from the initial inspection. These values are then used to generate the condition assessment and the cost estimate.

For the larger, network focused systems, the maintenance responses are categorized into common classes. These categories of maintenance reduce the effectiveness in assisting project level decisions, but they provide a platform to handle and reduce the voluminous data required for a large network system. The categories also ease the development of deterioration curves and cost estimates. Instead of working at the microscopic level of tracking deterioration of different types of distresses and specific costs of fixing each distress, the system can work from the macroscopic view of costs and general deterioration from one category to another. This method facilitates the use of data bases with historic data in determining deterioration and unit costs.

The decision concerning whether to categorize the maintenance options really depends on the level of management for which the system is designed and the needs of the user. Using the categories of maintenance method will more closely fall in line with the information present in the U.S. Army Corps of Engineer data base. The use of categories also eases the information collection requirement, but it sacrifices the possibility of precise, accurate cost predictions for each project.

F. Budgeting/ Work Prioritization

1. Objectives

Establishing well thought out maintenance policies and applying proper priorities is essential to making the system most effective. One of the most critical contributions that construction management can add to the development of the EDMS is to create an effective procedure for prioritizing the maintenance requirements based on the goals and needs of the user and the most prudent use of resources as established by deterioration models.

The system should be adaptable and flexible enough to predict budget requirements based on maintenance needs, or to schedule work loads according to budget constraints.

2. Techniques

In the article, "Pavement Performance and Life Cycle Cost Analysis," Tien Fwa and Kumares Sinha (1991) state that life cycle costing for pavements is developing as the most accepted technique for evaluating budget decisions. Most life-cycle costing processes consist of agency costs (pavement construction, maintenance, rehabilitation, engineering and administration costs, etc.) and user costs (travel time and vehicle operating costs, etc.). The authors argue that current life cycle cost analyses can be improved by considering pavement performance. They discuss two methods of quantifying the cost of lower pavement performance, such as conducting surveys to determine how much users are willing to pay for a better quality ride, or using toll fees and adjusting the charges to find out how much people are willing to pay for a better ride. The key to life-cycle costing and accurate and effective prioritization schemes is to precisely quantify user costs.

a. New Maintenance Computerized System (NEWMAI)

The NEWMAI system for work prioritization incorporates an economic analysis based on the results of data developed and collected in a 1988 national transport study for the Republic of Panama. The study developed a Vehicle Operation Cost (VOC) for three categories of vehicles, cars, buses and trucks based on different types of roads and terrain. The study developed a relationship between the vehicle operating costs and the PCI of the pavements. The program uses the VOC analysis to compute the economic cost of each road segment by multiplying the appropriate value for dollars/vehicle/mile based on the PCI by the estimated traffic/year. This calculation results in a total estimated VOC cost per year. The recommended maintenance repairs are then listed in an economic hierarchical order so

that the user can "draw the line at the level of available resources." This allows the user to identify predicted expenditures and to quantify the economic impact of not performing the needed maintenance (Berger, 1991).

b. Pavement Management System for Small Communities (PMSC)

The PMSC system uses priority ratings to help establish priorities for specific sections and also computes long range goals. The priority index (PI) is computed using the following equation:

$$PI = 1/PCI \times TF \times FC \times TR \times MF$$

PCI = Pavement Condition Index; TF = Traffic Factor based on average daily traffic; FC = Functional Classification Factor (arterials, collectors or local access); TR = Transit/Bus Route Factor; MF = Maintenance Factor based on most current maintenance strategy.

The user has the option to override calculated priority indexes if certain sections require priority considerations based on political or other importance. The system will compute the total cost of the identified maintenance requirements, or the user can input budgetary requirements or the number of years desired to meet long range goals. The system will then use the priority index to schedule future maintenance activities (Tavakoli, 1992).

c. Integrated Airport Pavement Management System (IAPMS)

The Kennedy Airport IAPMS establishes priorities based on a Maintenance and Rehabilitation Prioritization Scheme. The system considers structural and functional pavement condition and pavement rank in prioritizing maintenance and repair needs. The pavement

rank is based on use including runways, taxiways and aprons. The rank is identified as primary, secondary, tertiary or quaternary. Pavement rank is weighted as the heaviest factor in determining priorities. Structural condition is rated in two categories of less then five years of structural remaining life or greater than or equal to five years of structural remaining life. PCI ratings of 1 to 100 are broken into categories of 10 and 15 to establish priority levels. The system uses these priorities in the budget analysis to select the activities that will be performed in a given year. The analysis can be performed in a constrained or unconstrained budget mode and can forecast ten years into the future. The system has a report generator that graphs predicted budget expenditure and changes in PCI (Rada, 1992).

d. Reliability-Based System

Rafael Quimpo and Uzair Shamsi (1991) develop an alternate strategy for prioritizing the maintenance decisions for water distribution systems in the article, "Reliability-Based Distribution System Maintenance." The authors suggest that maintenance prioritization may be based on reliability criteria. Using reliability techniques, the water distribution system is examined and rated. The decision maker can then set an economically acceptable level of system reliability. When the system goes below the preset level, maintenance or repair actions are employed. The reliability of a system is defined as "the probability that it will perform specified tasks under specified conditions and during a specified time."

The water distribution system of a city can be reduced to an analytically tractable system that can be analyzed using reliability methods. The system is considered as a set of components that connect supply sources to a point in the system. The components are items like pipe segments, pipe joints, pumps, valves, and other control or regulating devices. The component reliability is based on survival functions and models that predict fail-

ures. The theory is based on the premise that the time to failure follows the exponential probability density function. Each component is represented by an arc, and the network is then represented as a system of arcs connected at junctions called nodes. The reliability analysis evaluates the probability that a specified node can communicate with another specified node. The network can be decomposed into elementary blocks of components for which the reliabilities may be determined individually and be used subsequently to calculate the reliability of the whole system or any subsystem. Formulas have been developed for computing block reliabilities and the blocks can be connected in series or parallel.

The authors define a step by step process of converting the water system into a standard stochastic network which include:

1. Calculation of component reliabilities using the exponential model;

2. Reducing the network into sets of reliability blocks;

3. Conduct network analysis by enumerating set and cut sets;

4. Calculation of node-pair reliabilities;

5. Plotting the reliability surface;

6. Making the maintenance decision.

The reliability surface of the network is investigated for low values. If values are lower than the preset threshold values, the nodes inside the region below the threshold value are studied. The components that are candidates for preventive or restorative maintenance are the arcs that are connected to the suspect nodes. This system, though complicated, is extremely useful for items like piping in water distribution systems because many of the components are either hard or impossible to inspect. The reliability method offers a

technique for predicting the failure rate based on historic data and established probability models.

3. Earthen Embankment Recommendations

Assisting in developing budget estimates and in prioritizing the maintenance work effort are some of the most valuable assets of the embankment dam management system. Being able to compare the pros and cons of different policies and strategies will help managers at all levels. Scheduling Maintenance working within the budget constraints, or predicting future budgets appear to relatively straight forward, once the deterioration model and cost estimates are accurately completed. This element is most enhanced by a report generator that produces reports and graphs that are easy to read and understand. The process of producing the appropriate information substantially depends on the outputs of the cost estimate element and the performance prediction element.

The prioritization element is also dependent on the desires and needs of the user. The simplest method would be to use the condition index as the priority for rating maintenance work. This element must be able to translate the maintenance policies and practices into an accurate priority listing and, as it is with pavements, there may be more considered then just the performance of the embankment dam. Both the PMSC and IAPMS systems have effective methods for translating management's policies into a functional priority list. For this element, there is little difference between the different types of systems. A priority index or table is just as appropriate for embankment dams as it for pavements.

While the future costs of each maintenance alternative are possible to determine, the benefits of repairing an embankment dam will prove much more difficult to measure.

Unlike pavements that directly effect the vehicles that drive on them, embankment dams have no direct effect in many areas. For the purposes of flood and erosion control, it is difficult to place a benefit on "the catastrophes that may be avoided". The difficulty in evaluating benefits might make a cost-benefit comparison, like the ratio that the BMS uses, meaningless.

A variation of the reliability based method might be the most useful technique in establishing maintenance priorities. This method would eliminate the use of the Markov Decision Process in the deterioration prediction element and it would emphasize the importance of repair before a possible failure occurs. This method would have the same difficulties in predicting costs of future maintenance. Having a complete data base of historic data is essential. Without the proper information the reliabilities cannot be accurately calculated.

V. Infrastructure Management Systems

A. General

The literature includes little about implementing infrastructure management systems. These systems include incorporating several different categories of infrastructure such as pavements, bridges, waste water disposal systems and facilities all in one system that assists in making the decisions on how maintenance and rehabilitation money and resources will be distributed in a community or area. Infrastructure management systems are the next higher level of evolution in the development of infrastructure decision support tools. These systems will eventually either work in conjunction with, or replace, the category-specific infrastructure management systems. It is necessary, then, to at least consider what the infrastructure management systems of the future will look like when developing a current

category-specific infrastructure management system like an EDMS. After all, the EDMS will quickly become obsolete in the not to distant future if it is not designed with the flexibility to element as a part of an infrastructure management system.

B. Current Technology

1. U.S. Air Force Academy System

In 1993, an article addressing the principles of a community infrastructure management system was an early attempt at establishing a complete infrastructure management system. W. J. Thornton and H. D. Ulrich (1993) discussed an Infrastructure Maintenance System (IMS) being analyzed for implementation at the U.S. Air Force Academy. The program has three basic objectives: develop sound needs-based budgets; avoid surprise equipment failures; and optimize the academy's operations and maintenance (O&M) budget. The infrastructure categories that must be managed by the system include: water distribution, wastewater collection and treatment, power generation, roads, airport facilities and more than 1,000 buildings. Most of the infrastructure is at least 30 years old and in need of repair. The existing IMS was not effective primarily because the data base was generally lacking descriptive information such as condition, location, age, nameplate data, expected life and operational data. The system was noted as deficient in three areas:

a. The ability to discretely identify a system or component below the total facility level;

b. The ability to incorporate janitorial and utility costs;

c. The capability to record and/or calculate maintenance costs.

The article does not describe the details of the proposed system but it outlines the principles used in developing the new system. The first issue addressed was to correct the

deficiencies in the data base. The new system incorporates an algorithm to calculate unit costs for maintenance costs. The system also compiles operational cost histories to improve the accuracy of the calculations. The article is the first to address the issues of developing a system for dealing with the peculiarities of managing numerous buildings. The information requirements for managing buildings are vast compared to bridges and pavements. The authors emphasize system simplicity for dealing with the voluminous information requirements. Past programs failed because the magnitude of information compiled was so overwhelming it was impossible to use. The system exercises Pareto's law that states that approximately 80% of the cost of any activity will normally occur in 20% of the components being studied. Only components that have a high impact on the annual budget are monitored in detail. The article also addresses the importance of establishing well-conceived maintenance policies before implementing them into the Infrastructure Maintenance System.

This type system is in its infancy and is greatly lacking in the sophistication of more developed Pavement and Bridge Management Systems. But pavement and bridge systems are evolving too. The next level of evolution for these systems is to be combined in a limited infrastructure management system like a highway management system.

2. Highway Management Systems

In the article, "Highway Management Systems: State of the Art," Markow (1995) explains that the new requirements and advancing technologies are forcing agencies to re-engineer their organizations and investigate new systems that combine different areas of control. One result of this re-engineering is that each of the current separate bridge and pavement systems will eventually be tied together to improve both information sharing and

work coordination. He addresses two critical issues which must be addressed in the development of an infrastructure highway management system.

The first issue addressed is how to integrate the numerous bridge and pavement systems so that information can be shared and work efforts can be coordinated. Geographic Information Systems (GIS) are being reviewed as potential platforms for the integration. GIS technology can be used to assign a unique position and location identifier to each pavement section and bridge. This information provides a means for connecting data through relational data bases. New technology is already available for linking different systems and data bases together even if they were created using different products. This future potential of GIS is an effective argument for using GIS in the data base for the EDMS. The potential for integrating data bases raises another critical issue. If an integrated data base is shared by several different systems, then someone must be charged with the responsibility of ensuring the completeness, quality, integrity and timeliness of the data in the data base. This issue will certainly cause conflict between the system managers and must be resolved early in the infrastructure management system design.

Markow also expects that the growth in understanding and the rate of technical advances will continue to increase. Infrastructure management systems must be adaptable with great flexibility designed into them so that they can accommodate:

    a. Changing repair technologies;

    b. Improved indicators of system performance;

    c. Better performance prediction models.

The new technology will significantly affect design and maintenance policies. Life-cycle costing and cost-benefit analysis will continue to increase in importance and objectivity. Arbitrary design standards for service life will be replaced with standards based on cost-benefit studies. All of these issues will have to be addressed as maintenance management information systems continue to evolve.

3. Integrating Current Systems

H. Lee and R. Deighton (1995) discuss guidelines for expanding an existing Pavement Management System into a more comprehensive Infrastructure Management System (IMS) in the article, "Developing Infrastructure Management Systems for Small Public Agency." The authors state that pavement management is a special case of the general problem termed the "asset depreciation" problem. The subsystems of an IMS should be category specific management systems. These subsystems all have common elements including:

    a. Inventory;

    b. Measure of quality of service;

    c. Needs Analysis;

    d. Project Selection;

    e. Impact of various funding levels.

The National Council on Public Works Improvement (NCPWI) defines eight categories of public works infrastructure including: highways, aviation, mass transit, water supply, wastewater, solid waste, waterways, and water resources. All these elements of infrastructure must compete for limited funds available for their maintenance and rehabilitation. The most efficient means of optimizing the use of these funds is to compare the benefit gener-

ated for each dollar spent for improvements in the condition and performance of each category of infrastructure using the following criteria:

    a. Physical Assets: Annual change in capital investment;

    b. Product/Service Delivery: Annual change in the infrastructure's ability to perform its function;

    c. Quality of Service: Annual change in the condition of the infrastructure;

    d. Cost Effectiveness: Services delivered per dollar spent on infrastructure.

Each category of infrastructure must have an individual management system to address the microscopic aspects such as capital investment requirements, safety implications and criticality of service within the subsystem. The IMS must address the macroscopic aspects of the infrastructure as a whole. Data management is critical, as data from the individual subsystems must be integrated with the umbrella IMS. The most efficient means of data management in transferring information from one system to another is to use a consistent location referencing system that identifies the location of each of the items of infrastructure. This system must be universal, and Geographic Information Systems (GIS) are being considered by most as the spatial data integration and presentation platform for IMS.

A small public agency must find the most efficient system for automated data collection and condition evaluation that can be applied to the different types of infrastructure. Once the data is captured, the performance of the infrastructure can be predicted using the most appropriate performance model such as: selection matrices, regression curves, mathematical formulas and expert decision rules. Decision-making procedures for selecting the most appropriate rehabilitation strategy must be adapted to accommodate the various types of infrastructure. Analyzing budget allocations should include comparing the cost effectiveness and quality of service provided by each element of infrastructure. An IMS

should also have a means of graphically representing the infrastructure as a set of networks. Automated mapping (AM) is recommended as the most effective spatial data integration tool for IMS. It can augment the existing data base management system to provide a capability to produce various maps as an end product. Further study is required to establish an inclusive and accurate relative benefit analysis across which different items of infrastructure can be effectively compared.

The article develops the launching point for establishing an all inclusive infrastructure management system. Making the transition from a specific management system to an overall system is very complicated and will require much more research and testing. Key points from this article are that an IMS must first be made up of subsystems that are fully operational. The EDMS must be designed so that it is compatible and can be incorporated into an IMS. Data management is demonstrated as being critical in establishing an IMS. The universal use of GIS for recording unique infrastructure locations appears very likely. The EDMS should incorporate the use of GIS and should consider the potential of using automated mapping so that the system is capable of working with the next generation of systems. Flexibility in being able to adapt to future technology is essential for the systems success.

VI. Conclusions and Recommendations

Infrastructure management systems definitely appear to be growing in use and importance. Recent advances in computer technology and data base applications make the use of these systems as decision support tools possible at every level of management. Restricted maintenance and repair budgets as well as the increases in available information

are forcing managers to rely on management systems to optimize the use of limited maintenance resources.

Highway managers have led the development of infrastructure management systems with pavement and bridge management systems. These systems, though based on relatively simple structures, are becoming increasingly more sophisticated and complex. The research and technology that has been developed to implement these systems can and must be adapted to develop infrastructure management systems for other types of infrastructure.

The development of an Embankment Dam Management System (EDMS) should take full advantage of the theories, principles and models that have been developed for pavement and bridge management. The system should be comprised of similar elements which include:

    a. Inventory and Inspection Procedures;

    b. Condition Analysis;

    c. Load Analysis;

    d. Performance Prediction;

    e. Scope of Work/Cost Analysis;

    f. Budgeting/ Work Prioritization.

These elements must be adjusted to take into account the peculiarities of embankment dams. The initial system must be based on cost estimates and prediction models that can be developed from existing historic data, but equally important, the system must compile the necessary current operational data so that better models and predictions can be

developed in the future. In developing the system, the designers must consider the delicate interrelationship between elements. Elements cannot be designed alone, they must be built on the inputs and outputs of the other elements.

The performance prediction element is the limiting factor for the system. The proper historic data must be collected and analyzed to develop prediction models that are precise and accurate enough to be useful to the decision maker. The designers must first decide whether it is possible to measure or model performance through performance indicators or if they must measure and model deterioration as is done for pavements and bridges. Developing the appropriate models will significantly add to the existing body of scientific knowledge. The model used for predicting performance will determine the potential for the accuracy of future maintenance repair cost estimates. The inspection methodologies and data base requirements must be sufficient to provide the information to evaluate the load analysis/environmental effects on performance. The system's performance prediction models must be able to account for differences in the change in performance due to the different loads and environment in which each dam exists.

Another critical issue for the development of the EDMS is the identification of repair activities. Embankment dams obviously will not require reconstruction or relatively frequent rehabilitation as with pavements and bridges. The spectrum of repair activities which constitute routine maintenance must be identified along with the trigger points that initiate these activities. Developing unit costs for these activities and adjusting the cost based on time, location and scope is a level of sophistication not found in any of the existing pavement and bridge management systems.

Critical to the identification of the scope of work, is the development and implementation of life-cycle costing and conducting cost-benefit analysis of the possible maintenance activities. The cost-benefit analysis may be difficult to apply to the repair of embankment dams, but life-cycle costing is essential. Using historic data and, possibly, computer simulations, models must be developed for the effects each maintenance activity has on performance. Managers are becoming increasingly more concerned with life-cycle cost rather than just initial costs. This area still requires significant research effort.

Once these life-cycle costs are determined, then the budget analysis should follow accordingly. One of the most significant attributes of the system should be the ability to test several different scenarios. Essential to the development of the budget is the system's capability to prioritize the maintenance requirements. The system designers must incorporate a method for transforming maintenance policies and practices into a priority index or other method capable of rank ordering the maintenance priorities.

Finally, the system must be designed with the flexibility to adapt to future Infrastructure Maintenance Systems and future advances in technology and understanding. The use of GIS for identifying embankment dam locations is strongly recommended. Inspection procedures are quickly changing, and automated inspections will soon be the standard method. The system must be capable of adapting.

Construction Engineering should begin research in three areas in order to continue the development of the EDMS. The first step in the research should focus on developing the potential "states" to be used in the prediction model. The research must determine whether it is more feasible to model future performance or deterioration. The current ABS

Data Base that the U.S. Army Corps of Engineers uses should be analyzed to fully identify the possible states. The complete list of possible maintenance actions and strategies must be developed and scrutinized. Unit costs for these activities can be developed and the process for adjusting these costs for time, location and scope should be developed. As this process is complete, the research should continue in developing the life-cycle costing analysis which should include a cost-benefit analysis. The other area of important research should focus on developing the budget/prioritization element. This area of research will require close coordination with the end user of EDMS system.

If the EDMS is established in accordance with the elements discussed above and incorporates accurate models, then the system will provide a tremendous asset to its users. Such a system will continue to be useful for years into the future.

VII. References

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