KEY ISSUES IN BRIDGE MANAGEMENT

Ir. Dr. Ng See King,
Bridge Unit, Roads Branch,
JKR

Abstract

Worldwide, there is a shift in focus of attention from constructing new bridges to maintaining existing ones. This is due to 1) bridges are coming of age; 2) fund is low and 3) public outcries over occurrence of a great number of catastrophic bridge failures. In Malaysia, managing bridges had been the monopoly of the Government until around 1984 when highways were privatized. Users and stakeholders of tolled highways, concerned over value for money, are increasingly exerting pressure for better level of service. Bridge management is fast becoming an important subject of discussion. This paper discusses key issues in bridge management. The aims are to provide an insight into the nature of bridge management and to indicate necessary research directions in bridge management.

I. INTRODUCTION

Bridges can become unfit for their intended purpose due either to structural deficiency or functional obsolescence. The former refers to bridges that have suffered physical damages or defects, or instability to such a degree that their reliability becomes questionable (see Fig. 1 & Fig. 2). The latter refers to bridges that were previously designed to a lower loading specification but are now expected to withstand a higher loading because of new requirements. In order that the existing bridge stock continues to function safely bridges need to be properly managed.

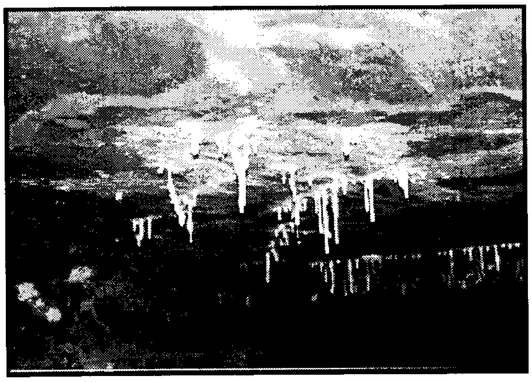

Fig. 1 Severe stalactites and lime stains at deck soffit due to water leaking through cracks at deck slab

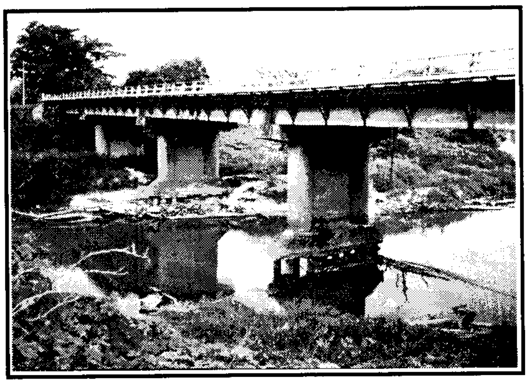

Fig. 2 General scouring at pier exposing the piles and threatening stability of the bridge

Looking after existing bridges has often been considered as lacking in glamour. Aspiring young engineers would prefer creating new bridges to maintaining ones already built. In creating new ones the engineers can claim 'ownership' of the bridges. To some, design and construction of new structures seem to demonstrate caliber of the engineer involved. Also, political paymasters, as a rule, often pay more attention to construction of new structures rather than existing ones.

There is, however, indication worldwide of a shift in focus of attention from building new bridges to maintaining existing ones [1]. This is due to 1) bridges are coming of age; 2) fund is low and 3) public outcries over occurrence of a number of catastrophic bridge failures. The great number of deficient bridges and the enormous amount of money needed to reconstruct them have prompted many bridge agencies to consider this two-pronged approach to *preserve the capital investment*:

(i) To find ways to extend the service lives of existing bridges; so as to postpone the need for total bridge replacement;

(ii) To seek optimal solutions to bridge problems so that scarce resources could be used in a more cost-efficient or cost-effective manner.

Approach (i) involves research for more durable materials and techniques for new construction and more effective system of bridge repair and strengthening. Approach (ii) could be called "a systems approach to bridge management" [2]. It looks at bridge-related problems in total and attempts to solve them globally using techniques transferred from many diverse disciplines of study:

- Bridge engineering
- Operations research/ management science
- Computer science and information technology

The focus of this paper will be on the systems approach. Our discussions will be arranged in the context of these three areas.

In Malaysia, there are over 6,647 bridges and culverts along federal routes; and perhaps, about the same number of state bridges [3]. The Public Works Department of Malaysia or JKR, as the technical arm of the Government has been entrusted the responsibility to manage these bridges. JKR, through a series of bridge related studies, has gained sufficient knowledge to become quite proficient in managing this bridge stock [4]. Thus, management of existing bridges has hitherto been the monopoly of the Government.

With the privatization of road projects in Malaysia since 1984 bridges are now also operated and managed by private organizations. There is likelihood that maintenance of federal roads in the peninsular Malaysia may be privatized early next year. A new scenario has already emerged where operations and management of bridges have become a business endeavor, road users being the customers. Toll operators very often adopt the "users pay" principle where payment in toll is proportionate to the benefits enjoyed by road users [5]. Since users and other stakeholders of tolled highways are always concerned with getting appropriate value for money concessionaires of tolled highways are increasingly under pressure to deliver high level of service. It is no wonder that bridge management is fast becoming an important subject of discussions in Malaysia; as is evident from the number of bridge related proposals (either for Government contracts or research funds) submitted to the Government for approval.

The purpose of this paper is to discuss key issues in bridge management. The paper draws on the author's experience in JKR and his research interests in bridge management systems (BMS) and bridge assessment. The targeted readers are managers and engineers who are involved in up-keeping bridges and researchers who wish to identify areas for research.

II. BRIDGE MANAGEMENT AND BRIDGE MANAGEMENT SYSTEM (BMS)

A. Bridge management problem

Bridge management entails a broad range of activities carried out to ensure that every bridge in the highway network remains fit for its intended use throughout its life span. These activities are inter-related and include:

- Planning, design and construction of new bridges
- Inspection and assessment of current bridge performance level
- Maintenance, repair and rehabilitation of bridges
- Operation and control of bridges

In order to effectively manage our bridges, important questions that need to be addressed are Which bridges are to be taken action, what actions and when? Fig. 3 depicts a conceptual model of the decision options [6]. Each box within the three axes represents an option of choice. For example, decision option I refers to replacing Bridge A in the first year. This option will be compared with other options in an optimization exercise.

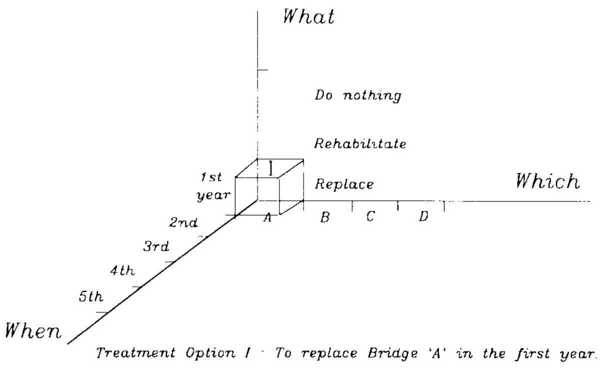

Fig. 3 A conceptual model of bridge decision [6]

The search for an optimal bridge decision is rarely made in one stage by considering all three issues simultaneously. Rather, optimal decisions are often made in two levels, namely, the network and project levels. In the *network level*, optimal solutions are sought among bridges in the network. This tackles the 'which?' issue. In the *project level*, optimal solutions are sought among various feasible treatments for specific bridges. This tackles the 'what?' and 'when?' issues.

In developing a decision-making scheme to address the above bridge management questions it is useful to look at the so-called "scientific method" of problem solving as shown in Fig. 4 [7]. The method begins with problem statement in which the nature of the problem is clearly stated. This will help in the identification of the objective and selection of the criterion of choice. The next step is gathering of data and enumeration of feasible alternatives. The fourth step involves determining or predicting the impact(s) due to each alternative. The fifth step is the ranking of all the alternatives in relation to the impact(s) each produces. Finally, the best alternative is chosen based on the principle of choice. We will refer to this scheme later in the paper.

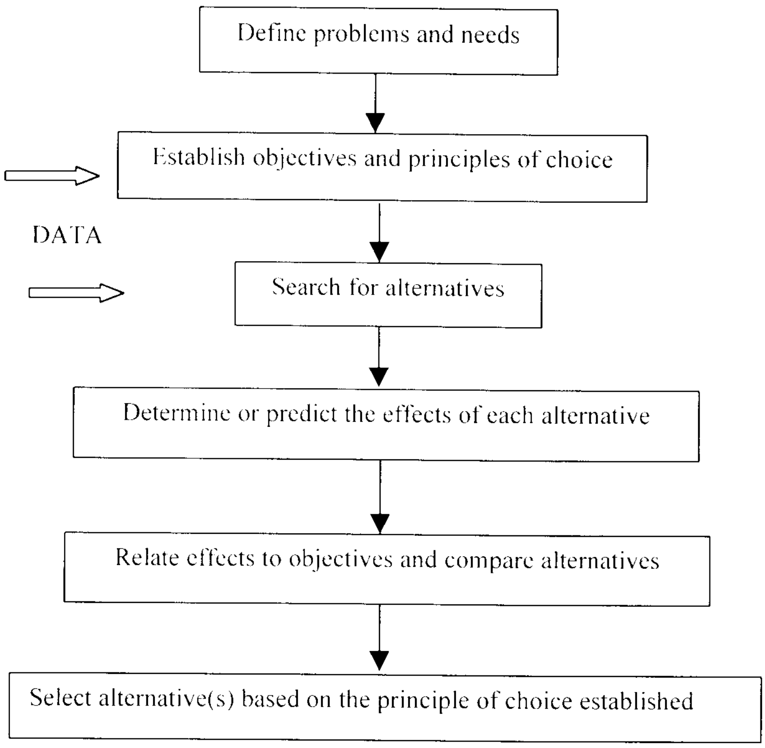

Fig. 4 The scientific method of decision making/problem solving [7]

B. Bridge management system (BMS)

The traditional approach to bridge management tends to be ad hoc. Bridges are planned and designed without much consideration of any future inspection and maintenance needs. Indeed, there is hardly any planned maintenance at all. Bridge decisions are often based on subjective appraisals of individual engineers and may not be timely or optimal. A systems approach to bridge management would overcome these weaknesses. It requires that a comprehensive bridge management system (BMS) be developed.

B1. What is a BMS?

Bridge Management System has been defined as [1]

> "... a tool to assist highway and bridge agencies in their choice of optimal improvements to the bridge network. [It] encompasses all engineering and management functions that are necessary to efficiently carry out bridge operations. These include data collection and management, inspection, planning, programming, construction and maintenance. A BMS also includes formal procedures for coordinating these functions and analytical tools for models to help identify bridge needs and establish priorities".

In short, a BMS serves these two main functions:

- Data management
- Decision supports

In order to achieve these functions, a BMS should have a structure consisting of the following components:

- BMS Software
- Staffing
- Manuals/guides

The *BMS software* consists of a suite of computer programs for managing and manipulating the data to provide decision supports in specific bridge decision problems. Its main components are the database system, the prediction model and decision model. The collection of data in a manageable database is indeed the core for any bridge management system. The *prediction models* make use of the data to make predictions about future performance and needs, and also the impacts under each treatment option. The *decision models*, on the other hand, make use of the predicted data to make optimal decisions.

Many people often think that the system software is *the* system. Indeed, the personnel operating and maintaining the software is also part of the overall bridge management system. There are numerous activities that could best or perhaps only practical to be performed by human. They include gathering of bridge data, bridge assessment and interpretation of the processed data.

The procedures to carry out bridge management activities must be standardized such that they are consistent and uniform. This calls for documentation of the procedures and work instructions for the staff. Besides being a major component of a BMS, these documents will also serve the *quality management system* of the organization.

B2. JKR BMS

JKR developed the nation's first computerized BMS in 1989 called JKR BMS [8, 9]. JKR BMS has been designed to aid bridge managers and engineers in the following activities:

i. Ranking of bridges for actions
ii. Selection of 'best' treatment options

iii. Bridge data management
iv. Project data management
v. Cost data management
vi. Preparation of annual budget
v. Control of abnormal vehicle movement

JKR BMS was developed in-house by bridge engineers for bridge engineers using dBaseIV database management system [9]. It is a pity that JKR BMS has not been fully implemented and only the *bridge information module* is used. The system has undergone a few improvements over the years [10] but the original DOS-based version remains popular because of its simplicity and tailor-made features.

It is useful to note that a BMS must always be customized to fit the needs of the organization. Tham et al [11] discusses how JKR BMS was conceived and developed as a business system and applying the techniques thereof.

II. KEY ISSUES IN BRIDGE ENGINEERING

Common bridge engineering activities include feasible bridge actions and activities to gather data prior to taking the actions.

A. Bridge actions/treatments

Basic decisions and treatments include bridge maintenance, repair and rehabilitation, replacement and posting of weight restriction. Ref. [12] classifies *maintenance* operations as ordinary maintenance and specialized maintenance operations. *Ordinary maintenance* operations are operations of a repetitive nature and in general, technically rather simple. The intervention level for an ordinary maintenance operation is often already established. *Specialized maintenance* operations are essentially repair work triggered by the results of a bridge inspection. Ordinary and specialized maintenance operations are thus commonly called collectively as maintenance and repair (M&R). *Bridge rehabilitation* is an extensive repair.

Whilst M&R and rehabilitation are more to restore the structural components for physical damages or defects, bridge strengthening is upgrading work to increase the load-carrying capacity of bridges. The bridge to be strengthened may be in good physical condition but was however designed to a lower loading specification. In many instances, under-strength bridges may not necessarily have to be replaced if known to carry only light vehicular loads. In such cases, it may be more economical to post the bridge with weight restrictions. However, weight restriction posting is not a common practice in Malaysia.

B. Bridge assessment

Prior to an action a bridge needs to be assessed of its current level of performance. An important point is in identifying an appropriate *performance measure* that would indicate or reflect the 'health condition' of the bridge and thus its needs. The performance measure would preferably be in a high *level of data measurement* so that meaningful comparison between two different values of performance measures can be made. A scale of data measurement can be thought of in terms of the amount of information it contains. *Nominal scale* is at the lowest level among other types of scales and is used for naming different category of performance levels. The value does not carry any meaning to allow comparisons to be made. The next level of data measurement is the ordinal scale. In the *ordinal scale*, the numerical values connote the order or rank notwithstanding by how much. For the *interval scale*, comparisons can be made based on the differences. *Ratio scale* is the highest level allowing comparisons to be made in ratios.

B1. Condition rating

Two common performance measures used in existing BMSs are condition rating and load rating. *Condition rating* can be in a nominal scale if used merely as a coding to represent each description of bridge condition. However, it is more often defined in an ordinal scale where the numerical values of, say, 1 to 5 do indicate the order, 1 being better than 2 and so on. In JKR BMS, condition rating of 1 to 5 is defined in the interval scale such that an improvement from 5 (the worst condition) to 4 has the same impact as an improvement from 3 to 2. Guidelines on condition assessment are provided in a national guide for bridge inspection by the Road Engineering Association of Malaysia (REAM) [13] and will not be further discussed here. Sufficed to say that due to simplicity condition rating will continue to be used as a performance measure in addition to load rating.

B2. Load rating

Load rating is the theoretical safe load-carrying capacity of a bridge expressed in respect of a standard vehicle. Load rating may be a better indicator of performance level as compared to condition rating [14]. Firstly, it can be objectively calculated rather than by subjective evaluation. Secondly, it is in a continuous scale rather than a discrete scale so it can assume any real value. Thirdly, it is a ratio scale rather than an ordinal scale and thus is more amenable to mathematical manipulation. The only problem is load rating may require involved calculations.

In fact, load rating is concerned with a different aspect of measuring bridge performance. It measures not just the capacity of structural members alone (as for condition rating) but the capacity in relation to live loads. This way, it permits use of site specific information, for example, types of traffic, in its evaluation. In many instances, for example, in posting weight restriction on bridges load rating is a better criterion for decision making.

A load rating exercise essentially involves comparisons of resistance and load effects. Major issues to be considered are lateral load distribution properties, definition of standard assessment loading and safety factors. In Malaysia, a procedure based on a JKR study [15] has been adopted. The procedure involves preceding rigorous analysis of all bridges in the network individually by *bound analysis*. Bound analysis is nothing more than simplified analyses treating the bridge superstructure separately as fully rigid and fully flexible. By bound analysis the whole bridge population can be categorized into three bridge groups: 1) Bridges which are *definitely* under-strength in terms of the legal load limits; 2) Bridges which are *definitely* capable of withstanding the legal loads and 3) Bridges which require further rigorous analysis.

REAM will soon prepare a national guide on determination of load-carrying capacity based on JKR practice. For the completion of the Guide, research is needed to study and recommend suitable reduction factors (for resistance) and load effect factors in a standard load-rating formula. Live loads known as LTAL and SV [16] are now the standard loading for bridge assessment. In view of the decision by JKR to replace Malaysia's very own bridge live load specification with British loading specification BD 37/88 [17] there is a need to review these assessment loads. In selecting an appropriate standard loading for assessment considerations must be made to the national axle load policy as reflected in the current Weight Restriction Orders [18].

Bridge inspection is an important activity in bridge management. Not only does it detect any bridge damages or defects prior to its manifestation it is the means to collect relevant data needed for bridge assessment and as inputs to a BMS. In some countries, field load testing of bridges is becoming an important activity for bridge assessment. Malaysia has not made field load test a routine exercise for bridge assessment although JKR has carried out a number of bridge load tests for various purposes [19, 20]. It is generally recognized that there will be enormous savings in sparing bridges from replacement based on a more precise assessment of their true performance levels by field load testing. In times to come, field load testing will become an indispensable tool for bridge assessment in Malaysia.

III. KEY ISSUES IN MODELING

A. Prioritization model

A prioritization model ranks the bridges (at network level) or treatments (at project level) in their orders of priority. Ranking is an old problem, which was devoted an entire chapter in the popular statistic book *Facts from Figures* that was first published in 1951 [21]. A key issue in prioritization is in the selection of the criterion of choice (see Fig. 2). There are broadly two types of criteria: 1) Effectiveness criterion and 2) Efficiency criterion. Effective criterion is concerned about the degree to which an alternative achieves a certain objectives while efficiency criterion is concerned about the value of return an alternative would bring relative to the amount of resources invested. It is important to note that efficiency criterion may not necessarily be a better criterion of choice than the effectiveness criterion. As a simple illustration, a shirt that doesn't fit may not be preferred to another one that fits (best achieve the objective) even if the former was offered a bigger discount by the store.

A1. Effectiveness criterion

One example of the use of effectiveness criterion is the prioritization module of JKR BMS [11]. The module uses the *worth assessment model* [22], which considers as criteria the following bridge attributes:

- Condition rating
- Carriageway widths
- Vertical clearance
- Average daily traffic (ADT)

Weightages are assigned to each of these attributes depending on the significance attached to them. The model furthers requires establishment of the decision-maker's *value systems* based on *utility theory*. A utility curve has priority points in the vertical axis and values of the bridge attribute in the horizontal axis. Every candidate bridge would be assigned a priority point based on its condition rating, carriageway width, vertical clearance and ADT respectively. The total priority point is the sum of all the points collected for each bridge attribute taking into consideration the weighting of the attribute.

It is interesting to discuss an alternative method devised by Mathematician Thomas L. Saaty called the Analytic Hierarchy Process (AHP) [23]. Professor Saaty argues that humans can rank a limited number of items in their orders of preference or priority. For ranking a big number of items we have to devise a strategy that begins with repetitive pair-wise comparisons of two items at a time. If we place the magnitudes of preference or priority obtained through pair-wise comparisons in a matrix, then the order of priority for all the candidates can be obtained by determining the largest eigenvectors of the matrix.

AHP can be used in diverse areas ranging from heart transplant candidate selection to football match winner prediction [23]. Use of this approach in bridge prioritization was initiated by Jiang and Sinha [24] from University of Purdue. In their ranking model, AHP is used to determine the weightings of bridge attributes in a worth assessment model. A slight improvement to this procedure based on Analytic Network Process (ANP) was made using JKR's bridge data as an example [25].

A2. Efficiency criterion

Efficiency can be simply defined as a comparison between outputs and inputs. For economic efficiency the comparison is between benefits and costs; or more correctly, discounted benefits and discounted costs. Discounting all benefits and costs that accrue during different timings of the bridge life cycle is necessary because money received at different points in time has different values – a concept known as the *time value of money*. The comparison can be made as a ratio as in *benefit-cost ratio*, or as a difference as in *net present value* (NPV). Alternatively, the discount rate *internal rate of return* (IRR) can be used. These are subject matters of *life cycle analysis* in Engineering Economics and a lot of references are available.

Economic efficiency is often used in selecting treatment option, that is, management at the project level. Further discussion of life cycle analysis will be made under decision models.

B. Performance prediction and bridge deterioration modeling

Because there is always a time lag between bidding for bridge funds and receipt of the approved funds, there arises a need to predict future performance and thus future needs. Also, in a rational decision-making process as discussed in Fig. 2 the impacts due to each strategy must first be predicted. The impacts from a bridge action are costs (and benefits) and extended service lives. Issues of cost estimates will be discussed later under cost data. For the prediction of extended service lives it is important to know how a bridge deteriorates over time. This can be achieved if a relationship between bridge performance and time is available. We call this relationship a *bridge deterioration model*.

B1. Deterministic models

Many existing deterioration models use a mathematical function relating condition rating and age. The function (known as performance curve) is often obtained by applying regression analysis [27] or *neutral networks* on historical bridge data. Because a deterministic performance curve is established and used, this type of model is considered a *deterministic model*. In the case of JKR BMS, a linear regression analysis is used to draw the best fitting straight line as shown in Fig.5 [28]. Future performance of a bridge or extended service life due to a treatment can directly be 'read off' from the curve.

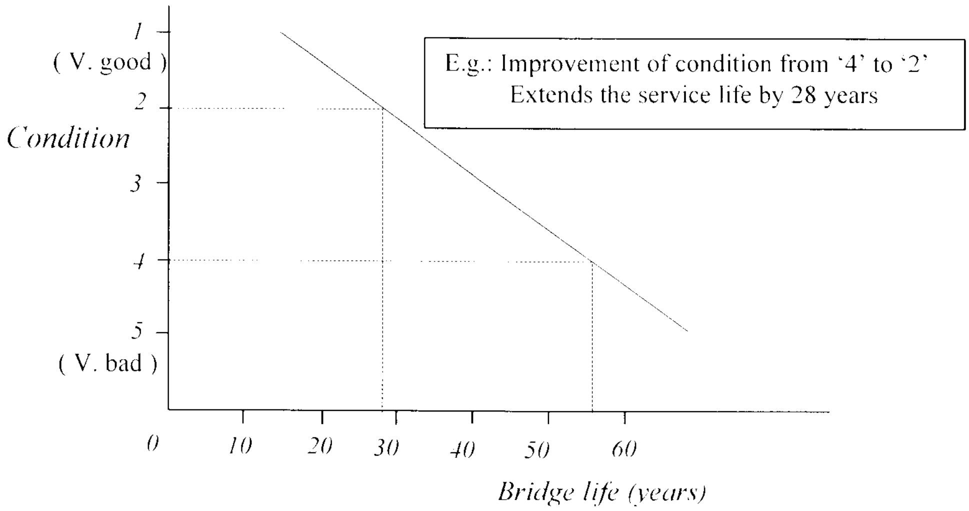

Fig. 5 Deterministic deterioration model [28]

The performance curve in Fig. 5 is continuous; which implies that the bridge condition is a continuous scale. It is however, customary to measure bridge condition by a discrete scale of numerical ratings. As such, a more realistic representation of the bridge deterioration process would be a stepped function as shown in Fig. 6 [29].

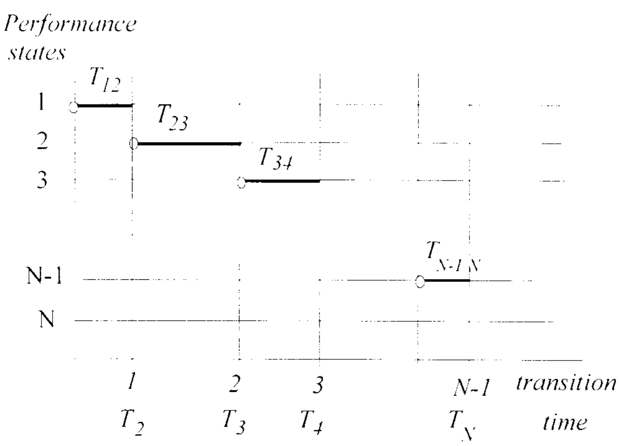

Fig. 6 A Sample function of the deterioration process [29]

B2. Stochastic models

In Fig. 6, the amount of time T_{ij} which the process sojourns or holds in state i before dropping to the next worse state j is known as *holding times*. We can assume that the holding times are deterministically defined and hence have a *deterministic* deterioration model. A *stochastic* deterioration model, on the other hand, treats the holding times as random variables. A stochastic model is clearly a more realistic representation of the natural process that occurs in bridge deterioration.

The deterioration process of a bridge as depicted in Fig. 6 can be modeled as a semi-Markov process. A *semi-Markov process* is a class of stochastic process whose transition from one state i to another j is governed by the transition probabilities p'_{ij} while its duration in state i before moving to state j is governed by the holding time distribution $h_{ij}(m)$.

A *Markov-chain* process is a special case of the semi-Markov process where the holding times are represented by geometric distribution (for discrete time) or exponential distributions (for continuous time). The concepts are the same for both continuous time and discrete time stochastic models and for the rest of this paper we will only refer to discrete time process. For the Markov-chain deterioration model, the deterioration process can be described by [29]

$$P' = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{1}$$

$$\boldsymbol{H}(m) = \begin{bmatrix} 0 & p_1^{m-1}(1-p_1) & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & p_{N-1}^{m-1}(1-p_{N-1}) \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \tag{2}$$

The transition matrix in (1) is obtained based on the observation that deterioration process is a non-increasing stepped function. The holding times $h_{i\ i+1}(m)$, $i = 1, \ldots, N-1$ in (2) are geometric distributed. However, a Markovian model is never expressed in the above formats. By taking advantage of the 'memoryless' property of geometric distribution the Markovian process is conventionally taken one step at a time and the deterioration process is characterized by a transition probability matrix of this format:

$$\boldsymbol{P} = \begin{bmatrix} p_1 & 1-p_1 & \cdots & 0 & 0 \\ 0 & p_2 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & p_{M-1} & 1-p_{M-1} \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \tag{3}$$

where p_i, i =1, 2, ..., N represents the probability of remaining in the ith state in the next step. We have assumed that the process would either stay in the same state or to the next lower state in one step. Notice that p_N is equated to 1 since N is an absorbing state and that when the process reaches this final state it will not move to other states.

There is now wide acceptance of Markov-chain deterioration models but the "memoryless" property underlying the geometric distributed holding times can be a problem. This property, used in the context of bridge deterioration, suggests that the probability for a bridge to move from its current state to another more deteriorated state does not depend on how long it has already been in the current state. Indeed, the requirement for geometric holding times should be relaxed to allow use of any distributions. The holding time distributions $h_{ij}(m)$ can be developed from historical data. Ng and Moses propose use of survival analysis to first determine the time to reach each state and then compute the holding time distributions from the difference of the times to two adjacent states [29, 30].

It is useful to note in passing that the above bridge deterioration models are commonly known as *empirical models* because they are developed from statistical analyses on historical data. An alternative type of model known as *mechanistic model* is also available.

B3. Prediction of future performance using stochastic deterioration model

For stochastic deterioration models, future performance is described by a *state probability vector*, which specifies the probability of the bridge being in each performance state. For Markov-chain deterioration model, performance of the bridge network at a future time m is calculated by using this relationship:

$$\pi(m) = \pi(0) \; \{ p_{ij} \}^m \tag{4}$$

where $\pi(m)$ is the state probability vector at any time m and $\pi(0)$ is the initial state probability vector. $\{ p_{ij} \}$ refers to the transition matrix as given in Eq. (3). The matrix $\{ p_{ij} \}^m$ is called the m-step transition matrix. In the case of the semi-Markov model, an equation analogous to that for the Markov chain is given in Eq. (5).

$$\pi(m) = \pi(0) \; \{\varphi_{ij}(m)\} \tag{5}$$

$\varphi_{ij}(m)$ is the interval probability matrix analogous to $\{ p_{ij} \}^m$ in Eq. (4). The formulation for $\varphi_{ij}(m)$ is slightly more complex and is given in [29].

C. Decision models

The basic treatment options that are available to a bridge engineer after he has conducted a detailed inspection on a bridge are:

i. To do nothing
ii. To rehabilitate
iii. To replace

There may be more than one feasible way of rehabilitating or replacing a bridge. As such, the engineer may consider several replacement alternatives and/or several rehabilitation alternatives. The question is what is the 'best' action? The basis for this decision is *life cycle cost analysis* considering all costs that may be incurred during the life cycle of the bridge. Discounted life cycle cost under each alternative option is worked out. The alternative with the lowest expected life cycle costs is considered optimal.

In order to do the analysis we need to predict the extended lives for each treatment alternative using a bridge deterioration model. Decision models based on deterministic deterioration models are called *static decision models*. Decision models based on stochastic deterioration process are known as *dynamic decision models* [31].

C1. Static decision model

The expected cost outlays under each alternative treatment option can be represented by a *cash flow diagram*. An example from JKR BMS [28] is shown here as an illustration. Fig. 7 (a) shows an example of the cash flow that would accrue should a rehabilitation option be selected. In this example, it is assumed that an initial rehabilitation work and subsequent yearly routine maintenance performed on the bridge would extend the service life of the bridge to 40 years. Fig. 7 (b) on the other hand is an example of the cash flow that would accrue should a replacement option be chosen. Also, it is assumed that an initial replacement of the bridge coupled with subsequent major rehabilitation work at the mid-life of 30 years and yearly routine maintenance would extend the service life of the bridge to 70 years. It is further assumed, in either option, that the bridge in question will subsequently be replaced with concrete bridges within an infinite planning horizon.

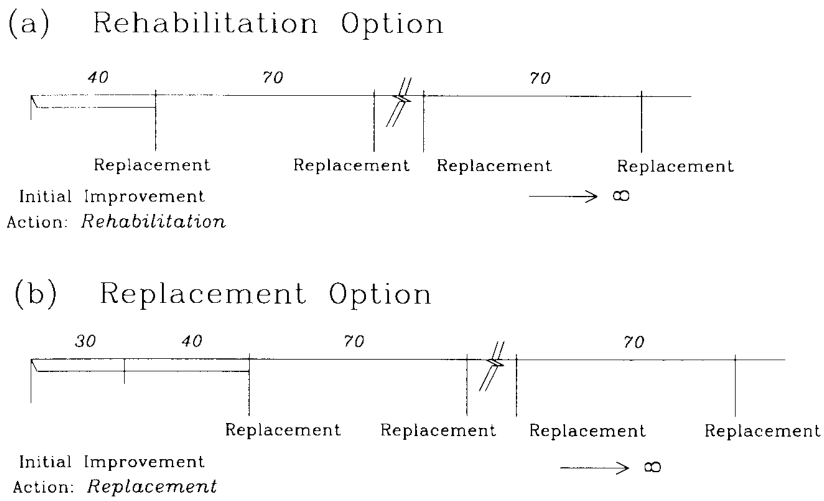

Fig. 7 Deterministic cash flow [28]

The decision model outlined above presumes that the costs as well as the extended service life due to an improvement work are known. In the JKR BMS, cost data from previous projects is kept such that standard rates are available for working out the costs.

C2. Dynamic decision model

A decision model is utilized to establish the optimal policy for the entire network of bridges. A *policy* is a rule that prescribes an action for each bridge condition:

$$R = \{ A_1, \ldots, A_i, \ldots, A_N \} \tag{6}$$

where A_i is the action prescribed for performance state i. Feasible actions for bridge treatments include the "do-nothing" option and various degrees of rehabilitation and reconstruction work. A policy is optimal if the discounted value of all the expected life cycle costs under the policy is minimal.

The dynamic decision model based on Markov chain deterioration model is called the Markovian Decision Process (MDP) [32]. Consider a planning horizon of n periods, if the process is in state i and action k is chosen, an immediate expected cost of ${}^kC_i$ is incurred. At the end of the first step, the process evolves to another state in accordance to the transition probability ${}^kp_{ij}$; after which the process starts all over again. The optimality equation is thus given by

$$v_i(n) = \min_k \left[{}^kC_i + \eta \sum_{j=1}^{N} {}^kp_{ij}\, v_j(n-1) \right] \tag{7}$$

in which $v_i(n)$ is the present value of the costs from the remaining n stages if the system is now in state i and the optimal selection of alternatives has been performed at each stage through stage n. η is the discount factor so that the present value of one unit of cost m periods in the future is η^m. η can be interpreted as equal to $\frac{1}{1+\varsigma}$ where ς is the interest rate. For infinite planning horizon where n is very large, $\lim_{n \to \infty} v_i(n) = v_i$, the optimality equation in this case is,

$$v_i = \min_k \left[{}^kC_i + \eta \sum_{j=1}^{N} {}^kp_{ij}\, v_j \right] \tag{8}$$

A number of methods are available for the solution of Eq. (8) but linear programming approach is often used [32].

The MDP is utilized in most of the state-of-the-art dynamic decision models. There are however some criticisms on this approach. One comment is that the formulation of the Markov chain approach considering one step at a time is computationally inefficient [33]. Another criticism is that the time-homogeneous assumption is not valid for bridge deterioration [27].

The Markovian decision process can be generalized to a semi-Markov decision process by [34]:

i. Allowing or requiring the bridge manager to choose an action whenever the system state changes, and not at fixed intervals;
ii. Modeling the system evolution in continuous time and not in discrete time;
iii. Allowing the holding time at a particular state to follow an arbitrary probability distribution rather than a geometric distribution.

Consider a planning horizon of n years: if the process just enters state i and action k is chosen, there is an annual maintenance cost of ${}^{k}M_{ij}(u)$ for the amount of time u after entering state i. The duration of remaining in state i is governed by the holding time distributions ${}^{k}h_{ij}(m)$. At the end of the first transition, a lump sum of ${}^{k}C_{ij}$ is incurred. The process next evolves to another state in accordance to the transition probability ${}^{k}p'_{ij}$; after which the process starts all over again. The formulation of the optimal equations is given in [35].

IV. KEY ISSUES IN ELECTRONIC DATA PROCESSING (EDP)

Although a BMS may not necessarily be computerized the advancement in information technology (IT) has much influence on today's bridge management systems. Different forms of data exist in bridge management: textual data, photographs, drawings, word or spreadsheet documents and maps. A host of database management systems are available in the market to cater for these data. In this paper, we will discuss issues related to the design and development of the database in the context of BMS.

A. Identification of bridge records

Each bridge record must be uniquely identified with a reference number. JKR adopts a referencing system that is compatible to existing management systems for pavement and slope so that future integration is possible. In this referencing system, a bridge *structure number* is derived from the Route Number followed by the distance of its location from the point of reference pertinent to the route. Thus, structure FT001 329/41 is located along federal trunk route No.1 and is approximately 329.41 km from the road origin, J.B.

Another recommended way of referencing a bridge is by Global Positioning System (GPS). This will facilitate use of Geographic Information System (GIS) technology in managing bridge data [36].

In JKR BMS, each bridge record in the database actually covers the data for a particular structural system at a particular bridge location. As such, a bridge consisting of two different structural systems, say, a two-span truss bridge system and a one-span RC girder bridge will be entered in the database as two records having identical reference number.

For privatized highways the number of bridges is not as large as JKR bridges. Further, it is necessary to monitor every span in order to ensure a good level of service demanded by users and other stakeholders. It is thus advisable to inventorize each span of bridge as a single record.

B. Types of bridge data (data element)

Bridge data can be conveniently categorized into:

- Bridge Inventory Data
- Bridge Condition Data
- Bridge History Data
- Historical Cost Data

Bridge inventory data include data that describe the bridges in terms of locations, types, sizes etc. They do not change unless there is a major rehabilitation or reconstruction. *Bridge condition data* include data that describe the bridge in terms of its physical conditions. Examples are load rating and condition rating. *Bridge history data* summarize the projects that had been completed on the bridge. Some details about the projects, like the year of construction, name of main contractor, etc., are among the useful information under this category. *Historical cost data* are the tendered prices of standard 'work items' in previous projects. A work item is basically a bid item in the Bill of Quantity expressed in a standardized format. One example is 'Lin.m Expansion Joint of Type A'. The states where the project is done and the year the tendered prices have been quoted are also stored in the records along with the prices. This will permit adjustment to be made on the unit rates to cater for geographical differences and inflation.

C. When is data updated?

In order that the BMS continues to operate the data needs to be current. Procedures must exist to require that data be updated in two instances, i.e.:

i. After a bridge inspection
ii. At the completion of a project

At the completion of a project, an as-built report will have to be submitted by site supervisory staff to the BMS *systems manager* for documentation. The report should include particulars of the project and any change in the inventory of the bridge. As-built drawings in AutoCAD are to be included in the submittal.

VI. CONCLUSIONS

This paper discusses key issues in bridge management. The diverse nature of the subject matter is demonstrated. Although bridges have been referred to in this paper, the materials do indeed apply to other types of infrastructure, for example, pavements.

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