Assessing Serviceability Improvement Alternatives of Existing Structures

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Abstract: The aim of this paper is to present a generic decision support system for selecting an optimal repair alternative for aging infrastructure systems considering sustainability. Emphasis is placed on how to properly decide on a maintenance, repair, rehabilitation, replacement strategy for deteriorating structures, applying the concept of life-cycle cost analysis. Taking into account the decision timing and repair costs of each alternative, an incremental annual uniform cost (IAUC) method is proposed to compare various levels of repair strategies and to reach a rational decision based on the proposed Economic Index (EI). On the sensitivity study of the model, it is concluded that the discount rate has minor impact on the selection and the repair timing is crucial to a successful saving. A priority ranking of repair alternatives can be identified once the deterioration model is defined, and the decision timing and repair cost are input. The proposed methodology provides engineers and owners with a quantifiable solution at project level for selecting repair alternatives with very minimal input information required.

Keywords: Cost engineering, Decision support system, Deterioration Structures, Life-cycle costing, Management methods, Mathematical modeling.

INTRODUCTION

The cost is essential when evaluating civil infrastructure construction and rehabilitation alternatives. Traditionally, accrued costs are expressed as equivalent to the present worth of costs or as equivalent to the uniform annual costs, using compound interest formulas [1, 2]. However, the formulation above has limited applicability when dealing with structural repair planning. It is because the service life after repair differs with respect to various repairing methodologies. Worst of all, the repair cost is a function of the natural and extended life of the degradation, location of the repair, end user cost accrued during obstruction. Hence, in this manner, it is well impossible to accurately estimate repair cost prior to the completion of the repair construction on civil infrastructures [3].

The timing on repair is also critical on the selection of improvement methods. After many years of service and numerous cycles of repair and rehabilitation, maintenance and repair costs for a facility often become excessive and safety becomes a serious concern. At this time, feasibility studies should be performed to determine whether to construct a new facility, replace, reconstruct, or disinvest portions of the existing structural system. A decision-making support system should also consider timing as a variation on making repair method selection. This can be accomplished through the linkage with deterioration models and the cost models so that the importance of decision timing is manifest. Preliminary results confirm that the repair cost is a function of time [4]. In other words, it costs more if the decision is delayed because more expensive actions will be required when dealing with aging structures.

Currently, most existing maintenance and management systems are developed on the basis of life-cycle cost minimization only [5, 6]. There exists no universally accepted, comprehensive methodology to assist owners and engineers at the project-level to achieve this goal [7]. Researchers have proposed various evaluation methods to replace conventional equations to justify new construction project with meaningful results [8]. Dealing with the complexity of the problem on existing structures, researchers applied genetic algorithms requiring large data base [9]. Also, researchers used stochastic methods in specific structures [10-12]. However, practitioners and owners need a simple, generic tool for preliminary justification when selecting repair alternatives. To make the idea a reality only the cost of the repair and the prolonged services life due to the repair actions are compared on the activity profile. To seek the greatest benefit at the least cost a quasi-operational indicator is defined. An incremental uniform annual cost analysis (IUAC) method is developed and proposed herein to help determine whether the proposed course of action is economically justifiable.

To accelerate the use of IUAC technique, this paper provides a user–friendly framework to assist decision makers building up a priority system on a spreadsheet application. The outcome also becomes an important piece of information for the public agencies to justify their decision on the repair priority not simply based on the initial cost but the minimum attractive add-in value due to the courses of action. The aim of the paper is to assist engineers defending their decisions in such a persuasive way when owners challenge a proposed repair cost. The methodology used in this paper also provides decision makers a convincing indicator why one particular repair is cost effective than others.

REPAIR ALTERNATIVES

In general, to achieve the research objectives, repair alternatives are divided into four major categories: do-nothing,

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cosmetic repair, limited rehabilitation and total reconstruction [13]. A "do-nothing" or "do minimum" is deemed the Base Level. At this level, no action is taken and therefore it results in zero investment in the remaining service life of a structure. The do-nothing option is frequently excluded either on instinct by project owners or by the profit-oriented consulting company. Little do owners know that experience has shown its validity and that it should be an option examined more explicitly. From the engineer's perspective, this option is often excluded because either the engineer has no involvement in future planning or the engineer lacks the proper tool to perform the analysis. Not doing anything at the moment and waiting until the right timing for a total reconstruction sometimes can become the most economical alternative in many cases. Being the simplest model among the four categories it also provides a comparative, base-line skeleton for three other categories.

The Second Level represents cosmetic repair, commonly deemed as surface level treatment, such as crack sealing of concrete or repainting of steel structures. The scope of repair is generally considerably larger than that of usual maintenance operation. Very minimal amount of effort is put in this repair alternative and it is limited to addressing where the deterioration is the worst. The cost is relatively low causing less disturbance than do the next two categories. The duration of the repair is usually manageable and the skill required at this level is cook bookish. The major disadvantage of this level of repair is that frequent reoccurrence of the same problem can be frustrating. Besides, the trade off on the low initial repair cost and relatively low tech repair sometimes brings lower quality of work and higher probability of experiencing the same issue in the next few years. People end up paying more throughout the service life of the structure by choosing this level over others.

The Third Level is defined as limited rehabilitation towards the whole structural system. It consists of restoring critical structural components to the service condition once constructed to postpone the replacement of the structure. Instead of minimizing the cost of repair as the previous level does, at this level, repair items focus on key components and details. The deterioration prevention mechanism tracks the cause of the problem will be emphasized at this level. A higher cost and larger impact during construction are inevitable. Nevertheless, the cumulative cost must not exceed that of the reconstruction. For the ease of analysis, the total cost of rehabilitation is assumed to be a fraction of the total reconstruction cost in this study. A lot of time, many facilities must remain where they are regardless whether the cost of rehabilitation is substantially higher than that of the reconstruction. They cannot be replaced at other locations because either the land is difficult or impossible to acquire. Even if the land were available at the time the cost of required environmental impact studies, and resolution of problems revealed them, would delay reconstruction for many years. A replacement project at a new location is sometimes considered unfeasible because the structure has historical or sentimental significance.

There is a fine line between the rehabilitation level and total reconstruction. Replacement in this context covers either a replacement of the total structure or major parts of a structure exceeding a quantity measure of 90% of the elements. A reconstruction may tend to cost more initially and yet can become the least cumbersome solution to repair problems. Several advanced materials have been developed ever since the structure was erected and state-of-the-art technology may offer a fast track, cost-effective construction that is more efficient than traditional construction methods. Owners or engineers may also want to take the opportunity to catch up with the latest design standard or change the functionality of the structure while choosing a reconstruction alternative. For instance, the seismic hazard map has been updated over the last two decades and the structure's owner may consider implementing the new design criteria to upgrade the safety for the occupants while reconstruction method is chosen. Yet there are cases where reconstruction is the only feasible solution because of excessive future maintenance projections.

DETERIORATION MODELS

Engineers deal with deterioration of structure shortly after its initial use. The way engineers appraise deterioration problems has evolved from the use of rule of thumb before 1980, to the implementation of stochastic models and deterministic models [14]. Based on "physical" parameters of structures, deterministic models describe the relationship between the factors affecting facility deterioration and the facility condition using a mathematical or a statistical formula. It could be as simple as a straight line approach used by Frangopol *et al*., [15]. Due to the uniqueness of an individual structure's nature and its environment, a calibrated deterioration model of its own can be worked out on a case-by-case basis. Huang *et al*., [16] in his study of maintenance strategies for concrete bridge decks successfully implemented the mechanistic model calibrated for Wisconsin using field inspection data. Mauch and Madanat used semi-parametric hazard rate models to depict the deterioration of a reinforced concrete bridge deck [17].

A typical element of a civil infrastructure system is likely to have a time related performance profile such as that shown in Fig. (**1**) where t_r represents the repair decision timing, t_i is when the time aging sign appears, and t_f represents the predicted service life reaching minimum acceptable condition with no repair. It is basically a quarter of an oval in the first quadrant where the horizontal axis represents time and the vertical axis the condition index, S, as percentage. For this study, the performance indicator, or "Structural Condition Index, S", is defined as the percentage of structural service condition at the time of repair with respect to the full service condition after construction. It can be formulated as follows:

$$S\,\% = \frac{(\mathit{Capacity\ at\ Evaluation} - \mathit{Min.\ Accepted\ Capacity})}{(\mathit{Full\ Capacity\ at\ Completion} - \mathit{Min.\ Accepted\ Capacity})} \times 100\% \quad (1)$$

The whole life performance profile shows the performance of an element from the time of its construction to the end of its functional life. At or beyond the point when the performance is considered critical, structural repair or strengthening becomes essential to restore reliability. When repair works are carried out prior to when the critical level is reached, a postponement of the critical condition will ensue.

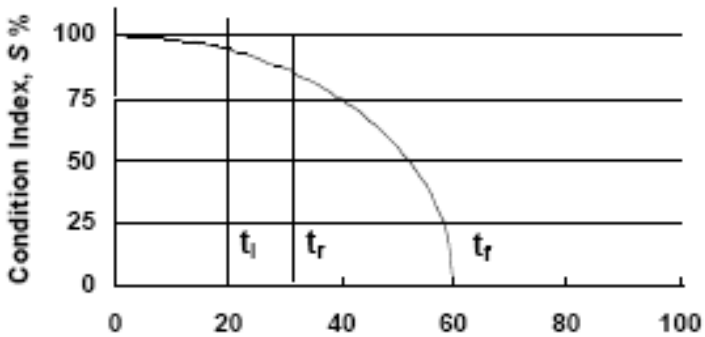

Fig. (1). Typical deterioration model.

MATHEMATICAL FUNCTIONS

Several assumptions are made in constructing the deterioration prediction curves in the study. The curve is defined as a quadratic function, simplified based on experimental data collected and paper reviewed [16-18]. The deterioration state is affected by many factors such as location, humidity and temperature. Therefore, these deterioration functions will need to be modified to reflect those factors where applicable.

The service condition Index, S is on a scale of 0 to 100. 100% represents a newly constructed structure. As it deteriorates, the percentage decreases and it finally reaches 0, indicating that the structure should no longer remain in service and requires reconstruction. Therefore, to successfully assess multiple solutions, the owner or engineer in-charge will need to determine the minimum level of serviceability. For instance, 60% of the capacity may be assigned as the least acceptable serviceable capacity. The total service life, t_f, is predicted and entered into the equation to construct the deterioration model.

$$\frac{t^2}{t_f^2} + \frac{S^2}{100\%^2} = 1 \quad (2)$$

where t represents time, the structural condition index can be obtained once t is entered.

EFFECT OF VARIOUS REPAIR ALTERNATIVES

An interim point, t_i, is defined as a "deterioration sign" at which the structural deficiency is observed through visual inspection. It happens somewhere between the time construction is fully complete and when a course of action is absolutely required. The basic concept of the structural repair effect is to show that the structural serviceability would respond differently with respect to each repair alternative. In the first alternative, the curve follows the quadratic equation with no changes since nothing will be done in the first alternative as shown in Fig. (**1**). In the second alternative, the curve will not switch paths until the repair is complete. At the initial point immediately after repair, its deterioration rate will slow down to the rate similar to that of the interim point, t_i. It is assumed that the cosmetic repair will only provide surface treatment and yet the rate of deterioration is continuous regardless of the repair. Then the curve progresses as shown in Fig. (**2**) where t_{el} represents the extended serviceable life after the repair, and t_{fx} represents the total service life predicted by the deterioration model. The deterioration curve simply shifts from point (t_i, S_{ti}) to (t_r, S_{tr}) after repair. The effect of the repair is more dramatic in the third level of repair as the deterioration curve will slow down after repair. The rate is assumed to be the same as it was at the time when newly completed. It is because after the major rehabilitation action is taken, the deterioration mechanism is also re-established. It is assumed that a repetition of the same deterioration curve is developed after repair as shown in Fig. (**3**). The deterioration curve shifts from point (t_0, S100%) to (t_r, S_{tr}) after repair. In the forth level the curve will move up to a 100% level after repair once the structure is totally reconstructed. The basic concept of the effect in the forth alternative is shown in Fig. (**4**). The deterioration curve simply shifts from point (t_0, $S_{100\%}$) to (t_r, $S_{100\%}$) after repair.

The extended service life is calculated using the deterioration prediction model. The deterioration rates prior to the repair are identical for all the alternatives. In the second repair alternative, the deterioration rate shifts from the time aging sign appears, t_i. The minor repair only recaptures the rate at which the initial deterioration starts. The deterioration time function after the course of action is as follows:

$$\% = 100\% \times \left[\sqrt{1-\left(\frac{t_r}{t_f}\right)^2} - \sqrt{1-\left(\frac{t_i}{t_f}\right)^2} + \sqrt{1-\left(\frac{t-t_r+t_i}{t_f}\right)^2} \right] \quad (3)$$

where t_r = repair decision timing, t_i = the time aging sign appears, and t_f = predicted service life reaching minimum acceptable condition with no repair.

Finally, the total service life after repair for the second alternative, t_{fx2}, is obtained as:

$$t_{fx2} = t_r - t_i + t_f \times \sqrt{1 - \left[\sqrt{1-\left(\frac{t_r}{t_f}\right)^2} - \sqrt{1-\left(\frac{t_i}{t_f}\right)^2} \right]^2} \quad (4)$$

where t_{fx2} = total service life predicted by the deterioration model of second alternative.

In the third alternative, the deterioration rate shifts from zero as it is when the initial construction is complete. The cross section loss cannot be recovered since there is no replacement to the structural components. Therefore the deterioration prediction model continues after the repair. The service condition percentage starts declining while the rate

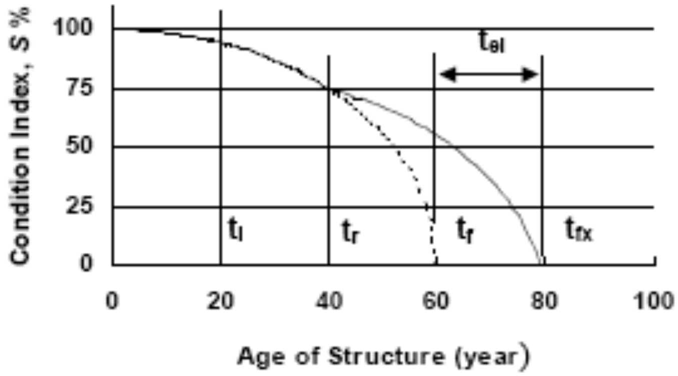

Fig. (2). Deterioration prediction model for alternative 2.

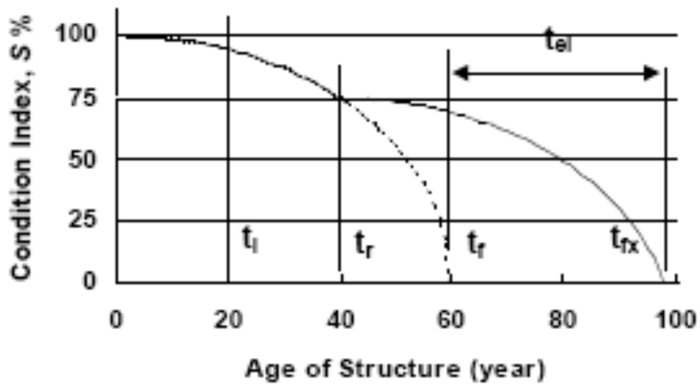

Fig. (3). Deterioration prediction model for alternative 3.

remains the same as a newly constructed structural member. The deterioration with respect to time after repair is as follows:

$$\% = 100\% \times \left[-1 + \sqrt{1 - \left(\frac{t_r}{t_f}\right)^2} + \sqrt{1 - \left(\frac{t - t_r}{t_f}\right)^2} \right] \qquad (5)$$

Then the total service life after repair for the third alternative, t_{fx3}, is obtained as:

$$t_{fx3} = t_r + t_f \times \sqrt{1 - \left[1 - \sqrt{1 - \left(\frac{t_r}{t_f}\right)^2}\right]^2} \qquad (6)$$

where t_{fx3} = total service life predicted by the deterioration model of third alternative.

In the last alternative, not only does the deterioration rate shifts back to zero, but the total service condition index is reset to 100% because the cross section loss is recovered. At this point, the deterioration prediction is likely to start over as a newly completed structure. The deterioration function after major replacement is as follows:

$$\% = 100\% \times \sqrt{1 - \left(\frac{t - t_r}{t_f}\right)^2} \qquad (7)$$

Lastly, the total service life after repair for the fourth level, t_{fx4}, is obtained as:

$$t_{fx4} = t_r + t_f \qquad (8)$$

where t_{fx4} = total service life predicted by the deterioration model of fourth alternative.

The extended serviceable life after the repair for various repair alternatives can then be calculated as:

$$t_{el} = t_{fxi} - t_f \quad i = 2, 3, 4 \qquad (9)$$

where t_{el} = extended serviceable life after the repair, and t_{fxi} = total service life predicted by the deterioration model for various alternatives.

The extended service life after repair can be calculated using these formulae. They provide the basic input for the cost model to perform the cost analysis. The effect of each repair is also used as one of the factors in determining the Efficient Index-(EI).

COST MODELS

Specific structural repair cost models are used in this paper. A structural repair cost model can be expressed as follows as described in the NCHRP Rep. No. 483 [7]:

$$TCC = PC + DC + CC + MC + RC + UC + SV \qquad (10)$$

For this paper, only the varying cost elements are taken into account to ease the analysis. P represents the initial cost of planning (PC), design (DC) and construction (CC). The repair cost (RC) is expressed in terms of a percentage to the initial cost P.

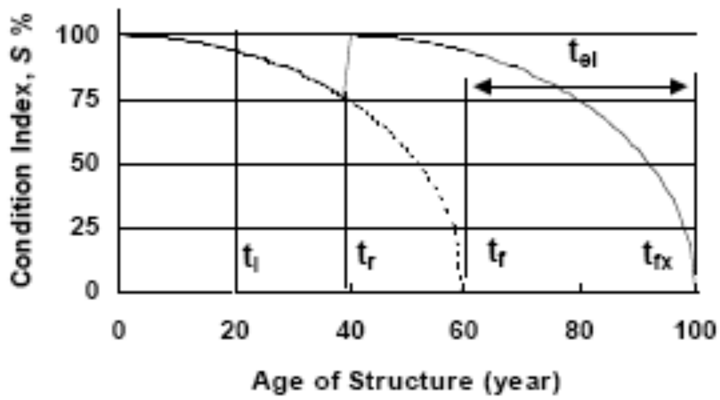

Fig. (4). Deterioration prediction model for alternative 4.

There are distinct differences between maintenance and improvement decisions. This is partly because the budget allocated comes from separate sources. They are independent in a way but interrelated. The recurring routine maintenance cost (MC) including preventive maintenance and general maintenance is difficult to predict. In the study of various repair alternatives of structures, the maintenance cost is a common denominator and therefore neglected in the comparison. This will be found insignificant later in the study.

The repair cost (RC) is a single input item in the cash flow diagram at the time when the repair is complete. Since the estimate involves too much uncertainty it is expressed in a ratio, R of the initial total construction cost of a similar structure, P. The user cost (UC), the value or the benefit of a structure, should be brought to users or stakeholders. It deserves detailed consideration. A sample of user costs calculation can be found in Liedtke, *et al.,* and Nishijima, *et al*., [19, 20]. The way to calculate the remaining value of an aging structure, the so-called salvage value (SV), needs to be clearly defined and enter into the equation.

ANALYSIS METHODOLOGY

The overall evaluation process begins with building the deterioration prediction model of one particular structure. Once the deterioration model is constructed, the engineer will need to perform a visual inspection and provide an appraisal of the current structural status rating. Then the remaining serviceable life can be calculated. The extended serviceable life of each repair alternative can also be obtained using the above formulae. Even though the initial cost P is the same for various repair alternatives it will need to be reserved from the diagram because the service life varies with different repair alternatives. AW_P is the equivalent annual worth of the initial construction cost. It will have to be distributed from the time zero to total extended service life, t_{fx}. The repair cost is considered as a second tier investment placed at the time after the decision is made. In this study, the initial construction costs and the repair costs are distributed during different time periods. AW_{RC} is the equivalent annual worth of the repair cost. It is assumed to be distributed from the time the repair is finished, t_r to the end of the service life, t_{fx}.

The problems associated with comparing multiple cash flow diagrams can be resolved by an incremental method. However, with very little or no information on the positive (income) side of the cash flow diagram, neither the “cost/benefit method” nor the “internal rate of return method” can be used to establish the base for comparison. Comparing various alternatives with only the cost information on a varying service life is a rather difficult task. There are too many variables involved in the formula and too many assumptions that need to be made without specific boundary [8].

To solve the problem an incremental uniform annual cost (IUAC) method is proposed. The first alternative–no repair is used as the base for comparison because it has no repair cost. Then the second alternative–cosmetic repair is compared to the first alternative. Next the third alternative–major rehabilitation is compared to the second alternative. Finally, the total reconstruction is compared to the third alternative. Only on the repair cost is emphasized. As addressed before, the initial construction cost plays a minor role in the overall decision making process because the service life of a structure is roughly a range between 50 and 150 years, and the service life extended by the repair is so much less than that estimate. It is negligible and yet cannot be totally excluded in the study otherwise the common denominator of the Cost Index (CI) will be zero. On the second tier investment, the repair cost, it is found to be a decisive factor in the cash flow diagram. In the fourth alternative, the repair cost becomes a 100% P at the time of repair, excluding the cost of demolition.

Finally, an economical index, a ratio of the cost to the benefit, can be built as follows:

$$EI = \frac{Cost\ Index, CI}{Life\ Extended\ Index, TI} \tag{11}$$

where *EI* = economical index

COST INDEX AND LIFE EXTENDED INDEX

A Cost Index, CI, is constructed to compare the alternatives in their cost aspect of repair. It has a basic formula of:

$$CI = \frac{(AW_P)_i + \lfloor (AW_{RC})_i - (AW_{RC})_{i-1} \rfloor}{(AW_P)_1} \quad i = 2, 3, 4 \tag{12}$$

where AW_P = Equivalent annual worth of initial construction cost, and AW_{RC} = Equivalent annual worth of repair.

For the first alternative, AW_P is simply the equivalent annual worth of the initial construction cost and AW_{RC} is equal to zero. AW_P can be calculated using the basic engineering economics formula:

$$AW_p = P\left(A/P\ i\%, n\right) = P \times \left[\frac{i\left(1+i\right)^n}{\left(1+i\right)^n - 1}\right] \tag{13}$$

where $n = t_f$, and P = initial construction cost. AW_P is also calculated using the same formula for other alternatives. For the repair cost, AW_{RC}, the basic formula is also used except $n = t_f - t_r$

The CI value is expected to exceed 1.0 for all the alternatives because any repair cost included in the cash flow diagram will cause the total AW to be greater than AW_1. Based on the preliminary study of the deterioration models, the serviceable life prolonged is a fraction of the whole serviceable life. A length of this magnitude over a whole serviceable life is rather trivial. Therefore, the equivalent annual worth of initial costs vary slightly with different levels of repair. The initial cost almost has no role in the study especially when the discount rate exceeds up to 5%. The repair cost, on the other hand, becomes a predominant factor in the decision.

An optimized repair method cannot be judged by cost alone. Therefore, a life extended Index, *TI*, is also created as:

$$TI = \frac{t_{fxi}}{t_{fx1}} \quad i = 2,3,4 \tag{14}$$

where t_{fx1} = total service life predicted by the deterioration model with do nothing, and t_{fxi} = total service life predicted by the deterioration model for other alternatives.

It is treated as the only benefit of the repair alternative where the total service life including the life before and after the repair. As addressed in the previous paragraph, the first alternative is used as a base for comparison. The prolonged service life is obtained using the deterioration models. The index is expected to be greater than unity for all the comparisons.

INTERPRETATION OF THE ECONOMIC INDEX

Finally the Economic Index, a ratio of the Cost Index to the Life Extended Index, is calculated for alternative 2, 3, and 4. It can be translated as the unit cost per extra life extended for each alternative. It can also be used to demonstrate the cost efficiency for each alternative.

$$EI_i = \frac{CI_i}{TI_i} \quad i = 2,3,4 \tag{15}$$

where EI_i = economical index for alternative *i*

A lower EI_j should be chosen for it is a more cost effective option. For instance, if EI_3 is greater than EI_2 minor repair is a preferred option than cosmetic repair. Similarly, if EI_4 is greater than EI_3 a major rehabilitation is preferred. The lowest EI value represents the most cost effective alternative.

APPLICATIONS AND DISCUSSIONS

The sensitivity of variables such as discount rates, decision timing, serviceable life prolonged, and repair cost of each alternative is analyzed. The difference between an interest rate and an inflation rate represents the real return on an investment; consequently, it is reasonable to use that difference as a discount rate, which is the policy of many agencies [21]. This rate is also the approximate long-term growth of the North American economy [22]. It becomes independent of repair alternatives when costs are expressed as equivalent to present worth of costs or as equivalent to uniform annual costs, using compound interest formulas on individual alternatives. From a practical perspective, structural life expectancy is normally between 80-100 years, not long enough such that the discount rate would become a significant differentiator amount various repair methodologies as shown in Fig. (**5**).

The decision timing plays an important role in the selection of the repair alternatives [4, 23]. The repair timing, t_r is expressed in the form of a percentage from the time aging signs appear, t_i to the end of useable life, t_f. The general relationship between three variables is as follows:

$$\% = \frac{t_f - t_r}{\left(t_f - t_i\right)} \times 100\% \tag{16}$$

where t_f = predicted service life with no repair, t_r = repair decision timing, and t_i = the time aging signs appear.

To illustrate the effect of repair timing, the repair cost of three alternatives versus decision timing is shown in Fig. (**6**). The repair costs are assumed to be 25%, 60% and 100% of the initial construction cost at midpoint of the t_i to t_f for the second, third and forth level, respectively. It is apparent that the benefit of making the repair action early is a tremendous cost saving. The consequences of delaying the repair can be up to 1.4 times the repair done at halfway before the end of service life.

Finally, the impact of the repair cost (RC), also the most important factor of the decision is illustrated in Figs. (**7**) and (**8**). To demonstrate the effect of the repair cost, the Economic Index, EI, of three alternatives are plotted with respect to the varying repair cost of rehabilitation (Alternative 3). The discount rate is assumed to be 3% and the replacement cost (Alternative 4) is assumed to be equivalent to 100% of the initial construction P at both figures. The cost of surface level repair (Alternative 2) is kept to a minimum at 5% of the initial cost P in Fig. (**7**). The most cost-effective option occurs at boundary of the lower bottom. For instance, major rehabilitation (Alternative 3) is the most cost effective option if the cost is kept below 35% of the initial cost of construction, P.

As the cost of rehabilitation increases to 70% of the initial cost P, surface repair (Alternative 2) becomes the most cost effective option. The replacement (Alternative 4) prevails as the cost of rehabilitation exceeds 70% of the initial cost of construction. A similar sketch is shown in Fig. (**8**) where the cost of surface repair (Alternative 2) is assumed to be 20% of the initial cost, P. It is apparent that alternative 2 is too high to be considered cost effective. The rehabilitation

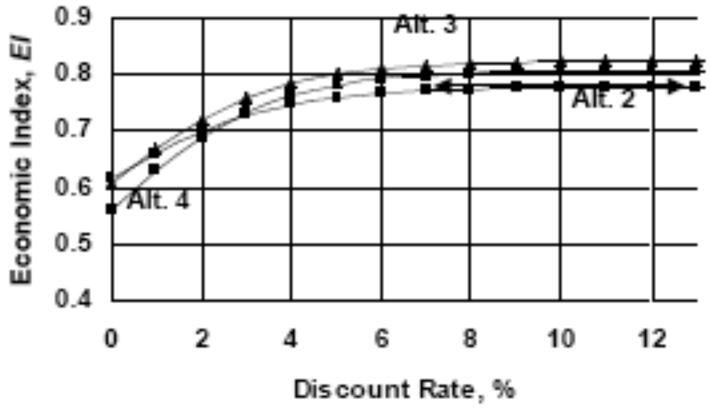

Fig. (5). Sensitivity of discount rate

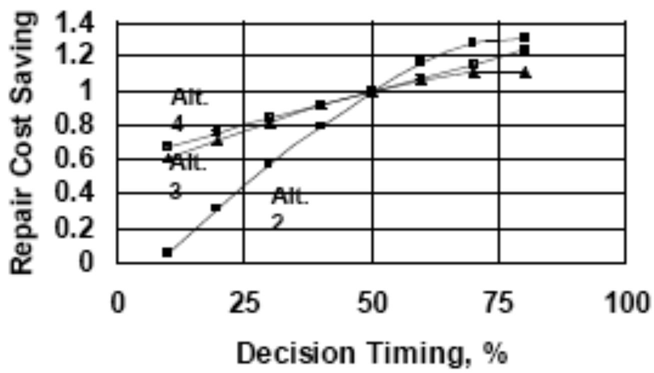

Fig. (6). Repair cost versus repair timing.

option should be chosen when it is less than 60% of the initial construction. Once the cost of rehabilitation exceeds 60% of the cost of initial construction, then a total replacement should be considered. In Fig. (**8**), results of the study generally agree with the rule of thumb quoted from the Seismic Retrofitting Manual for Highway Bridges [24]. Once the rehabilitation cost for a given structure begins to exceed 60 percent of the cost of a new structure, the economics begin to favor a replacement.

LIMIT OF THE DECISION MAKING TOOL

Several assumptions are made before building the procedure. The discount rate remains a constant throughout the life of structures because it is virtually unpredictable. It is assumed that there is no delay at the repair time after the repair decision is made. Also, the duration of the repair is neglected in the study. Uncertainties such as natural hazards, human error, or change of the functional demand are not included. Keep in mind that the all of the alternatives are subject to the same probability of the unexpected hazardous incidence. There should be no variation in the circumstances or environment of structures during and after the study period. The study is valid only when the environmental impact causing the deterioration stays constant. Any improvement of environment or lowering of demand can change the prediction. The deterioration function should be modified when change occurs.

None of the repair alternatives studied will improve the structural condition exceeding a replacement after repair. If, for instance as shown in Fig. (**9**), any change in the original design elevating the strength of the materials will cause the service condition rating to be greater than 100% of the original design and construction. The deterioration function can be revised to reflect that situation. Human factors have great impact on the decision-making process. In choosing an alternative for a given time period, there is no way to account for future decisions.\

CONCLUSIONS

There are a number of methods that researchers use to analyze life-cycle costs of infrastructure condition or rehabilitation alternatives including present worth method, annual cost method, rate of return method, benefit-cost ratio method and cost-effective method. The present worth method or net present worth (NPW) is believed giving reliable answers to evaluate construction and rehabilitation alternatives for infrastructure projects. However, for many infrastructure systems, the more money allocated to the repair the longer the service life is extended. The lump-sum yardstick comparison is misleading because it indicates that the total replacement will always be the alternative that extends the longest service life of a structure. To rectify the problem, researchers have cut the study period to 20 years or 30 years to perform a net present worth calculations. Supported by the sensitivity analysis, it is argued that actions undertaken beyond 20 years have no significant effect on economic efficiency calculations because of the effect of discount rate. Despite these matters, it is not adequate to cut

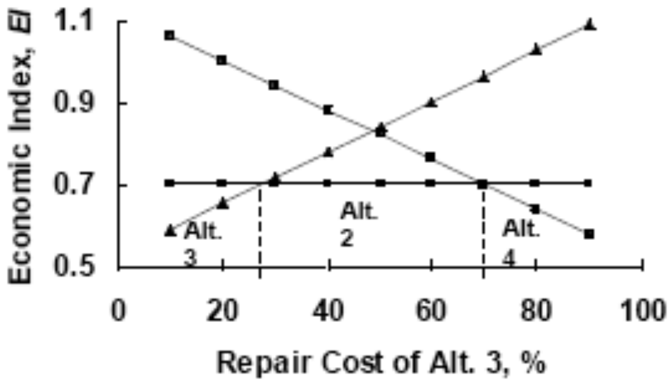

Fig. (7). Cost effectiveness chart – 1.

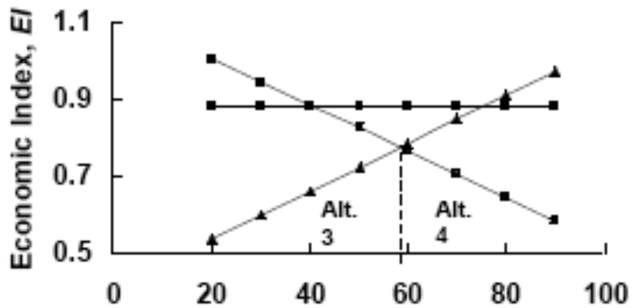

Fig. (8). Cost effectiveness chart – 2.

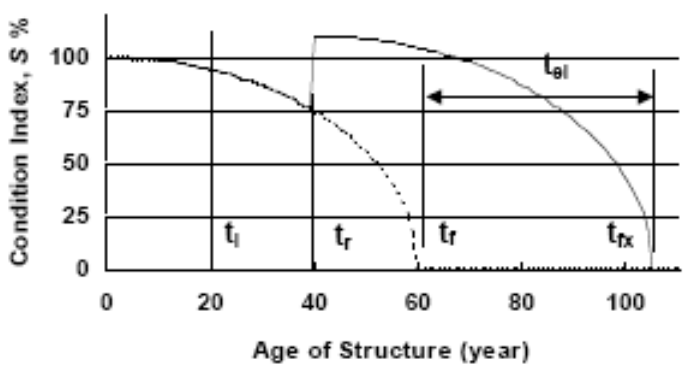

Fig. (9). Model for advanced alternative.

the study period to 20 years or 30 years to compare the repair strategies from a practical perspective.

The problems associated with comparing multiple cash flow diagrams are two-fold. First, the total service life of a structure varies with different repair alternatives. Comparing alternatives on varying longevity is common in engineering economics and can be easily solved by a uniform annual cost method. But the question is about how we can relate two variables, the investment and the benefit of repairs. It is very obvious that the more money invested in the repair the longer the service life will be lengthened. An incremental method should be used to examine whether the rates of increasing benefit are commensurate with the increasing investment.

Secondly, the problem is that quantifying the annual income or the net profit resulting from the existence of a structure is quite unrealistic. The residual value or benefit of an existing structure is almost impossible to measure. With very little or no information on the positive (income) side of the cash flow diagram, neither the "cost/benefit method" nor the "internal rate of return method" can be used to establish the base for comparison. It is the combination of these two issues that make the problem touchy. Comparing various alternatives with only the cost information on a varying service life is a rather difficult task. There are too many variables involved in the formula and too many assumptions that need to be made without specific boundary. Any imprudent assumptions will exaggerate the result to two extremes. To seek the greatest benefit at the least cost, a quasi-operational indicator is developed and proposed herein to help determine whether the proposed course of action is economically justifiable. It is a clear-cut, close-form solution to this problem.

In a world where financial resources do not keep pace with the growing demand for the maintenance of the deterioration of structures, it is imperative that those responsible for maintenance decisions make the best possible use of limited financial resources. A good decision is one that is based on logic, considering all available data and possible alternatives, and applying the quantitative approach as described in this paper. Occasionally, a good decision results in an unexpected or unfavorable outcome. But if it is made properly, it is still a good decision. Implementing a deterioration model tailored to specific structural characteristics, using the incremental uniform annual cost analysis approach, a decision maker is able to rank the cost effectiveness of various repair alternatives. This paper offers a clearly defined, easy to implement process to narrow down wild assumptions and unnecessary variables. It is concluded from the study that the discount rate has very limited impact on the selection of repair alternatives. Early repair is crucial to ensure substantial savings. A priority ranking of repair alternatives is achievable using the Economic Index (EI).

CONFLICT OF INTEREST

None declared.

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LIST OF NOTATION

AWP	=	Equivalent annual worth of initial construction cost
AWRC	=	Equivalent annual worth of repair
CC	=	construction cost
CI	=	Cost index
DC	=	design cost
EI	=	economical index
MC	=	maintenance cost
N	=	time variable
P	=	initial construction cost
PC	=	planning cost
RC	=	repair cost
SV	=	salvage value
S	=	structural condition index
TI	=	life extended index,
t_{el}	=	extended serviceable life after the repair
t_f	=	predicted service life at minimum acceptable condition with no repair
t_{fx1}	=	total service life predicted by the deterioration model for no repair
t_{fxi}	=	total service life predicted by the deterioration model alternatives *i*
t_i	=	the time aging sign appears
t_r	=	repair decision timing
UC	=	user cost

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