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CHAPTER 100

OPTIMUM MAINTENANCE STRATEGIES FOR HIGHWAYS BRIDGES[1]

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ABSTRACT

As bridges become older and maintenance costs become higher, transportation agencies are facing challenges related to implementation of optimal bridge management programs based on life-cycle cost considerations. A reliability-based approach is necessary to find optimal solutions based on minimum expected life-cycle costs or maximum life-cycle benefits. This is because many maintenance activities can be associated with significant costs, but their effects on bridge safety can be minor. In this paper, the program of an investigation on optimum maintenance strategies for different bridge types is described. The end result of this investigation will be a general reliability-based framework to be used by the U.K. Highways Agency in order to plan optimal strategies for the maintenance of its bridge network so as to optimize whole-life costs.

1. INTRODUCTION

As the existing stock of bridges continue to deteriorate, many countries, including the U.K., have to deal with the ever increasing demands on the limited resources available for their maintenance Das [1]. In recent years, a number of bridge management systems have been developed with the purpose of prioritizing the necessary work (Department

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[1] Proceedings from Conference on “Bridge Design, Construction, and Maintenance”, Singapore, October 1999. Thomas Telford, London, 1999 pp. 540-550.

of Transport et al. [2]; Hawk & Small [3]; Lauridsen et al. [4]; Söderqvist & Veijola [5]; Thompson et al. [6]; among others). The first very comprehensive reliability-based bridge management system supported by the European Union is described in Thoft-Christensen [7]. The basic principle on which some of these systems have been based is that an optimum network level maintenance strategy can be determined by recording the present condition states of the bridges and their elements and then using deterioration prediction models related to different maintenance regimes. However, as indicated by Das [8], the extent of bridge maintenance largely depends on the load carrying capacity of the bridges rather than on their condition alone. The implication is that estimates of maintenance needs should be based on bridge reliability rather than on condition states as defined in the current bridge management systems. Obviously, estimates of defects and deterioration are essential for determining bridge reliability.

In recent years there has been a search for including bridge reliability in the process of optimizing investments based on life-cycle costing (Thoft-Christensen [7]; Cropper et al. [9]; Frangopol [10]). Along these lines, the prime objective of bridge management is to determine and implement the best possible strategy that insures an adequate level of reliability at the lowest possible life-cycle costs or maximum life-cycle benefits.

The Highways Agency has to secure sufficient funds to enable it to maintain its structures in a safe condition. In order to justify these funds, the Agency needs to have an optimum strategy for the management of the trunk road network in England which includes some 16,000 structures most of which are bridges. Although the number of structures is modest compared to the national stock of some 150,000 bridges, the truck roads in England carry one third of all traffic and more than half of all lorry journeys; as such, the maintenance of the structures on the network is of considerable national importance (Das [12]).

2. BRIDGE MAINTENANCE

A strategic plan was proposed by the Highways Agency in 1997 to determine its bridge maintenance needs for the future. For a particular year, the strategic plan is intended to provide estimated levels of expenditure on both essential and preventative (also called preventive) maintenance work. The justification for carrying out essential work is that, without it the element would be unsafe, and hence if the work cannot be carried out for some reason, in the interim period safety measures such as width or weight restriction have to be employed. Such measures will cause traffic disruptions which can be estimated in terms of user delay costs. The justification for preventative work is that if it is not done at the time it will cost more at a later stage to keep the element from becoming critical. Also required as part of the overall maintenance regime is routine maintenance, which covers items such as inspections, drain cleaning and routine minor works.

In an ideal situation, the expenditure would be as shown in Figure l(a) (Wallbank et al. [11]). If however, insufficient funding were provided each year, the amount of essential work required for structures to remain in service would start to increase as shown in Figure 1 (b) (Wallbank et al. [11]). It is the purpose of the strategic long-term plan to identify the optimum expenditure profile.

Development of the strategic plan required the estimation of probability distributions for the maintenance intervals, preparation of typical maintenance costs, and application of the results to the range of bridge types and ages which make up the

Highways Agency's bridge stock. These stages are described in Wallbank et al. [11] and Das [1]).

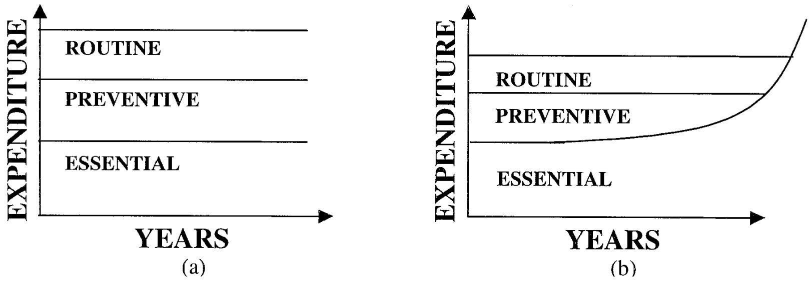

Figure 1. Bridge Maintenance Programs: (a) Ideal Bridge Maintenance Program; and (b) Effect of Long Term Underfunding (Wallbank et al. [11])

One of the most important items required for the implementation of the strategic plan is the probabilistic distributions of the rates of rehabilitation or replacement of the various bridge types with and without preventative maintenance applied to them during their lifetime. Also required are the probabilistic rates of applying maintenance actions such as repainting of steelwork. The bridge rehabilitation rates can be determined using three methods (Das [1]). The first, and the simplest, method is to base them on the expert opinions of experienced bridge engineers. This method was used by the Highways Agency for its first strategic plan in 1997. The second possible method is to collect available data on rehabilitation or replacement work carried out by the maintaining authorities in the past. The third possible method for determining bridge rehabilitation rates is by using reliability-based studies of whole life performance under different maintenance regimes. Bridge reliability analysis is essential for this purpose since there are many uncertainties in the lifetime process and these have to be dealt with in a rational manner. As shown in Figure 2 (Frangopol et al. [13]; Thoft-Christensen [14]), the uncertainty in reaching the critical (minimum acceptable) reliability level is affected by many uncertainties, including the 'as constructed' structural reliability, the damage initiation time, and the rate of reliability deterioration.

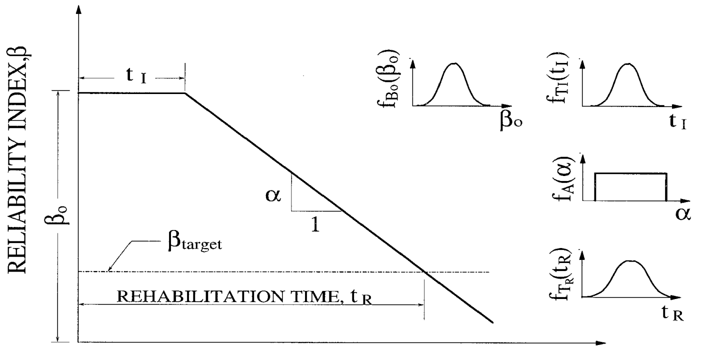

Figure 2. Bridge Reliability Profile and its Uncertainties (Frangopol et al. [13])

The predicted performance curve for any group of bridges will, with time related deterioration, reach the assessment (minimum acceptable) level of performance at some point in the future and when that happens the bridges will have to be replaced or rehabilitated (see Figure 2). The length of time from construction to the time of rehabilitation will obviously depend upon the reliability profile, which itself will depend upon the assumed maintenance regime. The probability distribution of that occurrence for the group (i.e. the time of rehabilitation) is the required replacement/rehabilitation rate for that bridge type. Such probability distributions were recently obtained by Frangopol et al. [13] and Thoft-Christensen [14] for steel/concrete composite and reinforced concrete bridges, respectively. A further type of uncertainty involves the average costs of rehabilitation and preventative actions which will be required to cost the different strategy options, and it will affect the final expenditure profiles.

As indicated in Das [1], the next step in developing the strategic plan is to, for each preventative maintenance scenario, multiply the numbers of bridges of each type constructed in a particular year, with the predicted rates of rehabilitation with and without (separately) preventative maintenance. This will provide the numbers of bridges to be rehabilitated in any particular year in the future. Similarly, the numbers of bridges are also to be multiplied to the rates of preventative maintenance to obtain the numbers of bridges in any future year which will have the corresponding maintenance action carried out on them. Finally, the last stage is to choose the best maintenance strategy for each bridge type.

3. OPTIMUM MAINTENANCE STRATEGIES

As previously mentioned, a project was commissioned in 1998 by the Highways Agency to determine optimum maintenance strategies for different bridge types. This section briefly describes the tasks of this project and presents some results. The four major tasks of this project are data collection, development of strategies, probabilistic modelling, and reliability-based optimization.

Data Collection

It was originally intended to obtain data from 24 typical bridges to reflect the main types (reinforced concrete, pretensioned concrete, post-tensioned concrete and steel/concrete composites) and different age groups. These bridges (see Table 1) were identified by WS Atkins [15] However; it was found that the Highways Agency's database did not contain appropriate data on maintenance history or present condition. Instead, unit costs were estimated for a series of maintenance options, based on data from current experience, as indicated in Table 2. The triangular distributions for these costs have three parameters which are represented by an ordered triplet (a, b, c), where a, b and c represent the minimum, mode and maximum values of cost respectively In addition, the numbers of bridges of each type built in each year were identified, as shown in Table 2.

Maintenance Strategies

The maintenance strategies for each bridge type and age group have to be based on results from earlier research projects and operational experience. The strategies include a "do nothing" strategy, involving no maintenance at all until repairs become essential. Also a "maximum maintenance" strategy has to be considered, whereby the bridge would receive frequent attention with the object of maintaining it in a pristine condition. The effect of essential maintenance is defined as the amount by which this activity improves the bridge reliability. The effect of preventive maintenance is defined by the reduction in the rate of deterioration and, in some cases, by improvement in the bridge reliability. A significant difference between essential and preventive

Table 1: 24 Bridges Selected by WS Atkins (1998)

ID. KEY	DESCRIPTION	YEAR OF CONST.	CAPACITY
	PRE 1955		
7914	1 span, simply supported beam and slab(cast iron/masonry) U/B	1929	3T ALL FEGp 2
7007	1 span Arched Masonry U/B	1840	40T ALL 33.8 HB
5549	3 span simply supported steel gdr & RC slab U/B	1926	40T ALL 45 HB
9455	2 span simply supported RC beam & slab U/B	1937	45 HB
	1955 – 1964		
1594	3 span continuous composite steel/RC U/B	1962	45 HB
966	5 span simply supported Insitu PSC beams & RC slab U/B	1963	45 HB
5289	3 span simply supported Precast PSC beams & mass conc. slab U/B	1958	45 HB
12075	1 span simply supported composite steel RC deck U/B	1962	40T ALL 30 HB
	1965 – 1974		
14451	Insitu RC Solid Deck Slab & Arch	1966	40T ALL & 37.5 HB
1150	Continuous Precast post tensioned & Insitu RC box beam with cantilever wings	1970	HA + 37.5HB
1741	Insitu concrete slab on rolled steel beams continuous across 6 spans	1966	HA + 45 HB
1174	Continuous Insitu RC solid slab	1966	40T ALL + 45HB
	1975 – 1984		
15785	Continuous voided Insitu PSC slab	1979	40T ALL or 45HB + AIL
15769	Continuous PSC voided slab	1975	HA
15767	Simply supported voided Insitu PSC slab with RC cantilever	1975	40T + 25HB
9507	Simply supported composite steel beam and RC slab	1979	HA + 45 HB
	1985 – 1994		
15974	3 span continuous composite steel/RC slab U/B	1990	HA + 45 HB
17996	1 span simply supported Insitu voided PSC deck U/B	1988	HA + 45 HB
12335	2 span arched brick/masonry U/B	1985	HA
18900	1 span simply supported Precast PSC and Insitu RC	1992	HA + 45 HB
	POST 1994		
N/A	7 span continuous steel U.B. composite with RC slab	1994	HA + 30 HB
N/A	Solid RC slab deck	1996	HA + 45 HB
N/A	Single span solid RC deck with integral abutments	1996	HA + 45 HB
N/A	Continuous 3 span solid RC deck with unbonded post tensioning	1996	HA + 45 HB

maintenance is that essential maintenance is normally undertaken when the bridge reliability has fallen to, or below, the target value, whereas preventive maintenance is undertaken when the bridge reliability is still above the target value. Fig. 3 (Frangopol et al. [13]) shows a comparison of present values of expected cumulative-time cost associated with three bridge maintenance strategies. Strategy A consists of essential maintenance only (i.e., two essential maintenances, A-E1 and A-E2, are used during the life of the bridge), Strategy B consists of preventive maintenance only (i.e., five preventive maintenances, B-P1 to B-P5, are used during the life of the bridge), and, finally Strategy C uses both essential maintenance, C-EI, and preventive maintenance, C-P1 and C-P2, during the bridge life-cycle.

Table 2: Estimated Maintenance Unit Costs at 1997/98 Prices (Triangular Distribution)

Maintenance Activity	Unit	Rate (pounds)			Frequency (years)		
Preventative Maintenance							
Painting	sqm	5	25	45	10	15	20
Deck Expansion Joints							
- maintenance	lin m	39	49	62	5	7.5	10
- Replacement	lin m	170	200	230	25	30	35
Waterproofing	sqm	16	23	34	25	30	35
Surfacing	sqm	15	22	32	25	30	35
Silane	sqm	15	20	25	10	15	20
Desalination							
Cathodic Protection							
- Temporary Support	lin m	6000	7000	8000			
- Concrete Repair	sqm	1800	2200	2600			
- Install CP System	sqm	150	200	250	20	30	40
- Maint. Of Anodes	sqm	70	100	130	7.5	10	12.5
- Inspection	sqm	20	30	40	7.5	10	12.5
Minor repairs	sqm	1300	1800	2300	10	15	20
Bearing Replacement	no.	1000	1500	2000	25	30	35
Essential Maintenance							
Concrete Repairs							
- Bridge Deck	sqm	500	900	1300			
- Crossbeam	sqm	500	650	800			
- Column	sqm	200	300	400			
- Abutments	sqm	600	1000	1400			
- Piers	sqm	300	700	1200			
Parapets							
- Upgrading	lin m	18	24	28			
- Replacement	lin m	68	90	119			
Replacement							
- Deck	sqm	100	200	300			
- Crossbeam	lin m		22000				
- Column	no		450000				
- Pier	sqm	1000	1300	1600			
- Tendon							

Note: Costs exclude VAT

Table 3: Bridge Stock by Year of Opening and Type

Year Opened	Reinforced Concrete		Post Tensioned		Pre Tensioned		Steel/Conc. Composite		Other		Total	
	UB	**OB**	**UB**	**OB**	**UB**	**OB**	**UB**	**OB**	**UB**	**OB**	**UB**	**OB**
<1955	262	2	1	1	6	0	107	3	345	2	721	8
1955	6	0	0	0	0	0	2	0	2	0	10	0
1956	15	1	0	2	0	1	5	0	1	0	21	4
1957	13	1	0	2	2	1	6	0	0	0	21	4
1958	21	0	0	3	1	1	6	2	0	0	28	6
1959	82	93	3	2	2	2	12	4	0	0	99	101
1960	62	18	9	10	8	7	16	7	0	0	95	42
1961	43	11	11	11	11	6	18	5	1	0	84	33
1962	96	47	21	12	11	11	29	29	0	0	157	99
1963	48	25	12	8	8	9	9	10	0	0	77	52
1964	37	9	8	14	12	20	18	8	0	0	75	51
1965	82	35	26	18	23	23	13	37	1	0	145	113
1966	102	25	27	5	12	12	18	8	0	0	159	50
1967	98	59	32	22	30	10	12	32	0	0	172	123
1968	60	12	18	13	25	19	29	25	1	0	133	69
1969	84	33	14	6	40	9	30	74	0	0	168	122
1970	122	78	99	20	53	54	19	53	0	0	293	205
1971	105	68	78	10	74	30	29	88	0	1	286	197
1972	56	32	27	4	41	25	10	29	0	0	134	90
1973	63	40	17	9	44	33	19	32	0	0	143	114
1974	103	81	30	19	48	49	20	11	0	0	201	160
1975	131	110	61	25	58	53	18	18	0	0	268	206
1976	85	61	13	10	38	33	16	10	0	1	152	115
1977	72	45	13	5	19	21	17	4	0	0	121	75
1978	57	40	31	1	24	48	17	11	1	0	130	100
1979	39	51	20	3	17	11	10	2	0	0	86	67
1980	38	44	6	4	28	37	9	9	0	0	81	94
1981	51	27	19	6	18	12	13	3	0	0	101	48
1982	53	41	10	5	13	13	14	8	0	0	90	67
1983	48	22	12	2	23	26	8	2	0	0	91	52
1984	43	56	10	1	16	18	3	5	0	0	72	80
1985	55	29	6	5	51	27	14	15	2	0	128	76
1986	42	53	8	1	26	13	12	10	0	0	88	77
1987	26	24	8	2	22	8	10	14	0	0	66	48
1988	52	38	10	5	19	7	10	6	0	0	91	56
1989	35	26	11	1	23	13	8	6	0	0	77	46
1990	55	60	35	4	25	3	27	23	1	0	143	90
1991	51	56	9	2	24	10	15	25	2	0	101	93
1992	48	58	8	1	21	3	18	13	0	1	95	76
1993	31	8	9	1	15	5	20	14	0	0	75	28
1994	22	13	9	0	2	6	5	18	2	0	40	37
1995	45	22	3	0	7	0	23	24	1	0	79	46
1996	10	3	0	1	4	4	11	13	0	0	25	21
1997	23	13	1	0	1	2	19	3	0	0	44	18
1998	0	0	0	0	1	0	0	0	0	0	1	0
Total	**2672**	**1570**	**745**	**276**	**946**	**695**	**744**	**713**	**360**	**5**	**5467**	**3259**

Note: UB = Underbridge, OB = Overbridge

'The optimum maintenance strategy is obtained by choosing the least expensive present value of expected cumulative cost. As shown, the optimum maintenance strategy is time dependent.

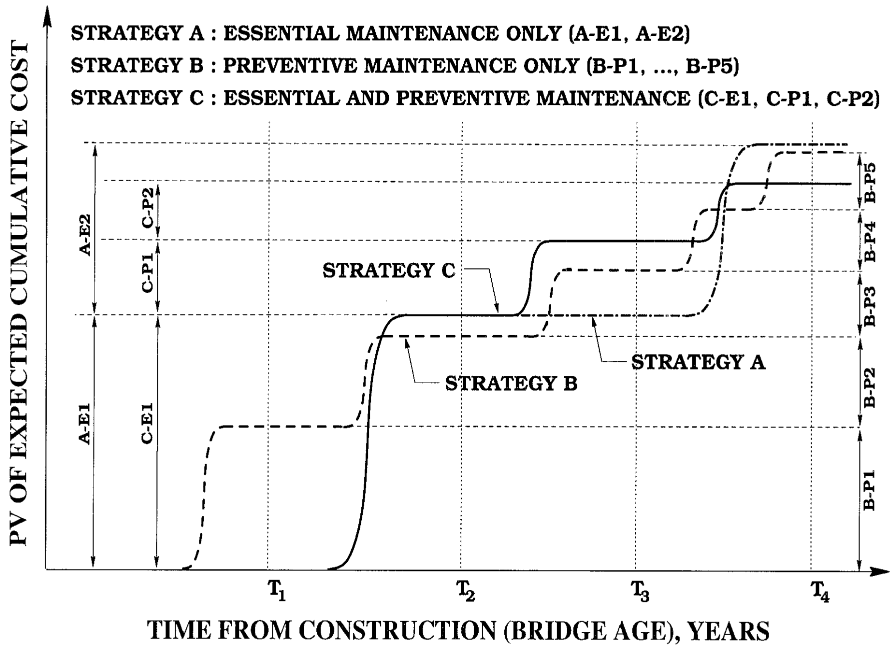

Figure 3. Present Value of Expected Cumulative Costs for Three Maintenance Strategies (Frangopol et al. [13])

Probabilistic Modelling

In order to find the optimal maintenance strategy for each bridge type, the present value of the expected cumulative cost of maintenance with and without preventive maintenance has to be obtained. As a first step in this computation, the probability of rehabilitation has to be obtained. Figure 4 shows the probability of rehabilitation for four bridge types assuming no preventive maintenance has been done (Frangopol et al. [13]). The computation of these probabilities is based on triangular distributions of

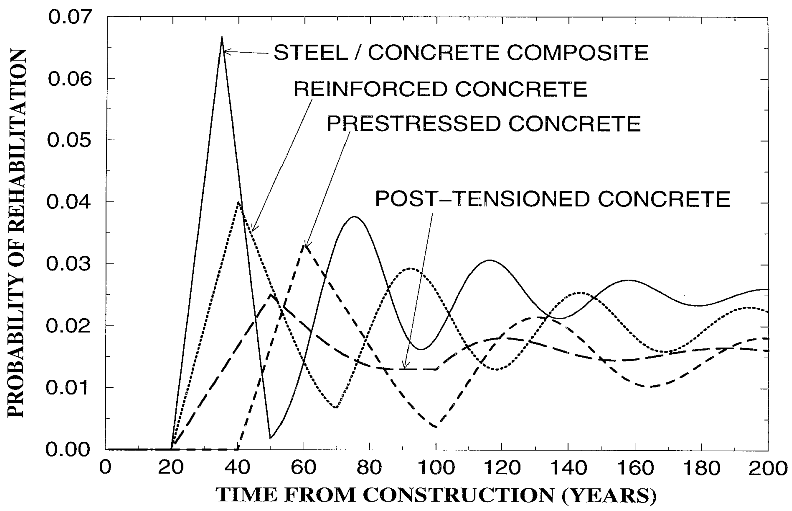

Figure 4. Probability of Rehabilitation of Four Bridge Types assuming No Preventive Maintenance has heen hone (Frangopol et al. [13])

rehabilitation rates predicted by experts for two different situations: (a) first rehabilitation assuming no preventive maintenance has been done; and (b) second rehabilitation assuming no preventive maintenance has been done.

As previously mentioned, a rational method for determining bridge rehabilitation rates is by using reliability-based studies of whole-life performance. Considering the case of first rehabilitation without preventive maintenance, the probability density functions of rehabilitation rates for steel/concrete composite (Frangopol et al. [13]) and reinforced concrete (Thoft-Christensen [14]) bridges were obtained. Figure 5 shows these functions assuming a target reliability level of 4.6. Research efforts are now in progress in Boulder (see Frangopol et al. [13]) and Aalborg (see Thoft-Christensen [14]) to obtain the probability density functions of rehabilitation rates assuming preventive maintenance has been done.

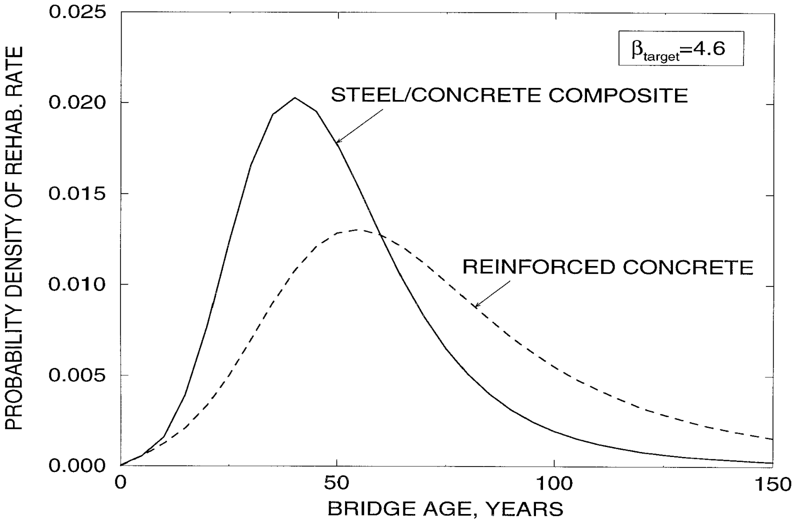

Figure 5. Probability Densities of Rehabilitation Rates for Steel/Concrete Composite Bridges (Frangopol et al. [13]) and Reinforced Concrete Bridges (Thoft-Christensen [14])

Reliability -Based Optimization

To implement the best reliability-based maintenance strategy for each bridge type, the minimum expected life cycle cost solution has to be found. Whole-life costs have to be discounted using accepted rates (Tillie [16]; Vassie [17]). A considerable amount of sensitivity testing has to be undertaken, so that the effects of changed parameters on the optimum solution can be examined.

4. CONCLUDING REMARKS

The program of an investigation on optimum maintenance strategies for different bridge types and some preliminary results has been presented. With the recent progress in the probabilistic approach to bridge lifetime reliability prediction, the implementation of these concepts is now practically possible. It should be emphasized that increased data expected in the future may properly be reflected in the whole-life bridge optimum maintenance process by re-evaluating the uncertainties and updating the solutions.

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