

PREDICTION AND ANALYSIS OF DETERIORATION OF MOSCOW BRIDGES

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ABSTRACT: Adequate description of deterioration of structures and their elements is very important for the effective use of the BMS. In the course of exploitation of Moscow BMS, deterioration processes have been studied using the results of standard inspections of 1,059 facilities. The analysis shows that for structural SE, deterioration of strength properties virtually does not occur or is of accidental character. In most cases, deterioration is attributable primarily to the wear of materials, which depends to a large degree on the quality of their manufacturing and protection. Also, lifespan prediction for a set of SE should take into account their mutual effects on each other. The methodological sequence of adjustment of deterioration models for different SE, initially adopted on the basis of experts' judgments, is suggested.

The main objective of a bridge management system (BMS) is to ensure optimal planning of repair and rehabilitation activities and to establish a budget for it. Within most BMS, this objective is attained on the basis of deterioration models, which describe wear of structures and their elements in the course of time in quantitative terms, using both probabilistic (Thompson & Shepard, 1993) and deterministic (Kuznetsov et al., 2003) prediction methods. As a rule, most systems consider only one type of deterioration model for all structural elements. In the BMS of the city of Moscow, deterioration of each SE is described as an exponential relationship of wear in the course of time:

$$I = e^{\lambda t} - 1 \quad (1)$$

where t is the time and λ = the rating coefficient determined for each SE on the basis of the boundary condition:

$$\lambda = \frac{\text{Ln}2}{T_c} \quad (2)$$

T_c is the average life of a given SE assigned using historical data of bridge management [3]. For the purpose of inspection the continuous function is being replaced by a step-like function, because the SE condition is assessed on the basis of a five-point scale [4]. The visual signs of wear corresponding to certain condition categories are given in the general BMS catalogue for each SE.

Once the condition of all SE is known, it is possible to determine the technical condition index of the entire structure as follows (Shepard & Johnson, 1999):

$$H_{\text{brg}} = \frac{\sum(H_{ej} q_j C_j)}{\sum(q_j C_j)} \quad (3)$$

$$H_{ej} = \frac{\Sigma(k_s q_{js})}{\Sigma(q_{js})}, \quad (4)$$

$$k_s = 0.5(3 - s), \quad (5)$$

where q_j = the number [units of measurement] of standard elements with a serial number “j” assigned for a bridge; C_j = the cost of complete rehabilitation of “j” standard element; s = the index of the condition category; q_{sj} = the number [units of measurement] of “j” standard elements having condition “s.” With an equal distribution of the total number of elements between all condition categories $H_{ej} = 0.5$.

The BMS of the City of Moscow was implemented in 2002. Since than 1,059 facilities (bridges, tunnels, pedestrian bridges, embankments, etc.) containing in total over 17 millions of SE of 215 various types has been inspected. Accumulation of this experimental data allows for initiating verification of the adequacy of deterioration models, previously adopted as regulatory models on the basis of experts’ judgments.

At first, an analysis of inspection results has indicated that there is no significant correlation between the age of a given facility and its technical condition index (Figure 1).

Zhang et al. (2003), who have also noted a similar effect, link this absence of correlation to the validity of presentation of a structures deterioration in the form of Markovian process, in which the wear intensity of an SE is dependent only on its current condition and independent of its past history (Ventzel & Ovcharov, 2000). We believe, however, that the results obtained should be attributed to the fact that selective repair activities compensate for different rates of bridge wear, which depends, to a substantial degree, on the following three main factors:

- Quality of manufacture of an element / bridge;
- Specific design features predetermining various mutual effects of SE on each other;
- Degree of protection of a structure against external impacts.

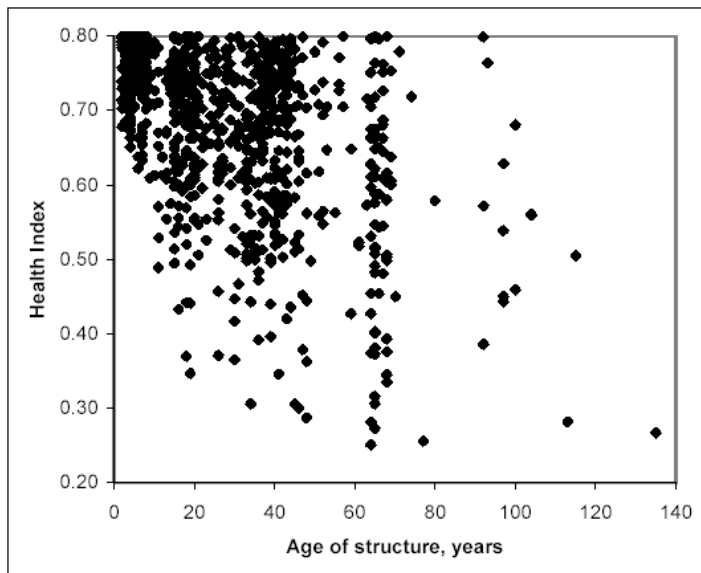


Figure 1. Values of technical condition indicator for bridges of different ages (Data for 1,059 bridges in City of Moscow)

Therefore only the repair actions that change either the quality of elements (replacement of an old element with a new one) or the conditions of exploitation (such as the installment of waterproofing) have an effect on the wear intensity.

To verify this assumption, which leads to a significant modification of adaptation procedure for deterioration models, we carry out an analysis of variations of the condition states values for different SE in the course of time.

The law of condition changes has been determined as a trendline for a set of points on the graph of $COND_{med} = F(t)$, where $COND_{med}$ is the medium condition category of an SE under study at time t_i . It has been assumed that the baseline point is the year of construction or rehabilitation of a bridges/SE, if any.

The medium condition category was determined as follows:

$$COND_{med} = \frac{\sum(COND_i N_i)}{\sum(N_i)}, \quad (6)$$

where $COND_i$ = the condition category of the i -th SE; N_i = the number of SE.

Each array of SE had been attributed to the exact bridge. Correspondingly, the number of arrays, which have been analyzed can be determined as a multiplication of the of the quantity of bridges and the quantity of SE types.

The actual values of λ_{real} have been determined in agreement with a procedure for adaptation of baseline data, by computing an actual residual service life to failure and a corresponding rating coefficient based on a specific inspection finding in the course of the BMS operation as follows:

$$\lambda_j = \frac{\ln(0.4*Cond_{medi} + 0.7)}{(t_j - T_{0j})} \quad (7)$$

$$T_{life,j} \geq k_r T_{life,j0} \quad (8)$$

Calculated in this way, the projected wear of every SE is analyzed by the methods of mathematical statistics, through determining the means, classified intervals, variance coefficients etc., as well as analyzing the cases where the wear parameters went beyond these intervals.

The results obtained suggest a conclusion that strength deterioration (fatigue) of most bearing or frame structures does not become apparent even during periods compatible with or exceeding the service life prescribed by regulatory deterioration models (Figure 2, lower curve). In an overwhelming majority of cases, deterioration of bearing and frame structures has been caused by wear of material due to corrosion of reinforced concrete and steel, which led to decrease in their working cross-sectional area. The reported scatter of condition categories is attributable mainly to variations in the properties of material and its protection (Figure 2, middle curve). Another cause of the scatter can be traced to the occasional, infrequent and unpredictable emergency situations, such as collision of vehicles with bridge structures, errors in the design or imperfection of the design development norms and standards (Figure 3).

For SE referring to construction materials, scatters of condition states are significantly more pronounced (Figure 4). This can be explained by variations of parameters of particular materials (in case of SE “Reinforced concrete”- different grades of strength, frost-resistance and impermeability), their initial properties dependent on both the manufacturing conditions and the quality of secondary protection under a given operational environment. In general, with an irregular scatter of points, it becomes difficult to find any correlation between the degree of wear and the time parameter. But the scatter for each array is far smaller so, in order to avoid a significant prediction error, deterioration models for such elements should be corrected for each facility considering the experimental data obtained from the inspection.

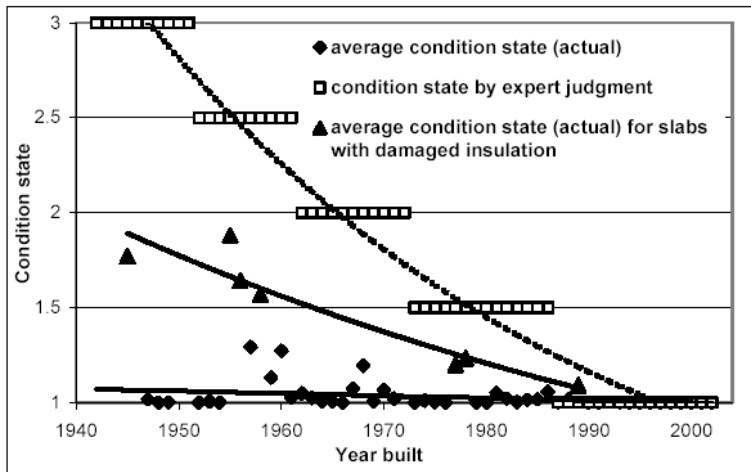


Figure 2. Deterioration of standard element 6060 "Reinforced concrete slab"

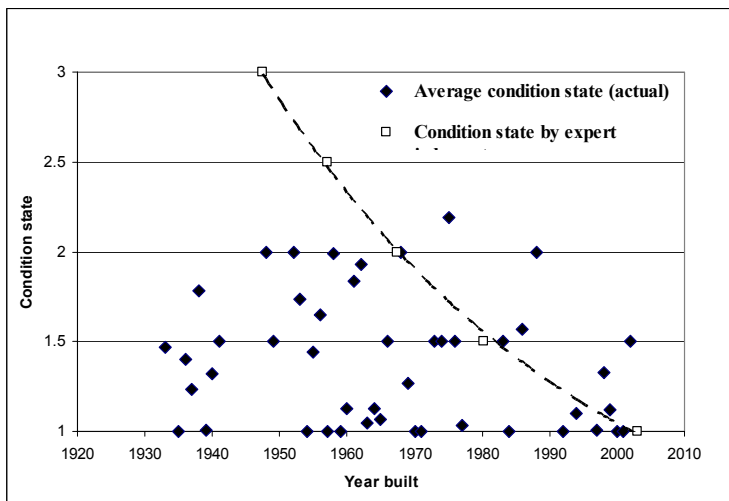


Figure 3. Deterioration of standard element 4050 "Stone Parapet"

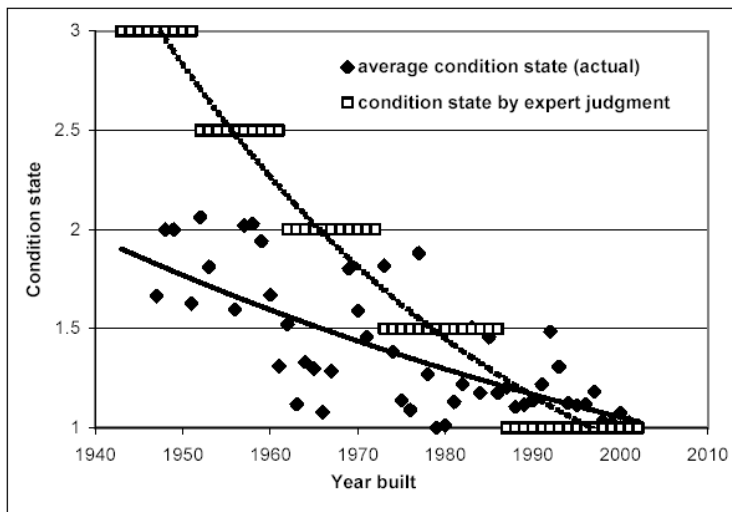


Figure 4a. Deterioration of standard element 1020 "Reinforced concrete"

For elements with a limited service life, e.g., for expansion joints, the regulatory deterioration models are very close to reality (Figure 5).

Summarizing the results obtained, we can subdivide all SE into 4 groups (Table 1):

- a. SE, the deterioration models of which can be assigned on the basis of mean values obtained in the process of bridge operation without taking into consideration specific design features or specific conditions of a region, like SE “Filled movement joint”. This model can be determined as “Exponential”;
- b. SE, the deterioration models of which can be assigned on the basis of mean values obtained in the process of bridge operation but should be adjusted taking into account specific design features of a bridge and/or specific conditions of a given region, as well as operating conditions, for example, SE “Reinforced concrete ledge” and most of the materials like “Steel” or “Reinforced concrete”. Deterioration model for these SE had been determined as “Fan-shape” one because of corresponding look on the graph;
- c. SE, deterioration of which is caused only by accidental situations, and repairs of which should be predicted based on the probability of accidental failures, such as SE “Steel beam”. The model can be determined as “Zero”, because BMS would not predict any regular deterioration for such SE;
- d. SE, deterioration of which depends on wide array of factors, which cannot be specified based on current knowledge. For these elements, for example, “Reinforced concrete column”, stochastic deterioration model, characterized by transition probabilities (Thomson & Shepard, 1993) would be the best.

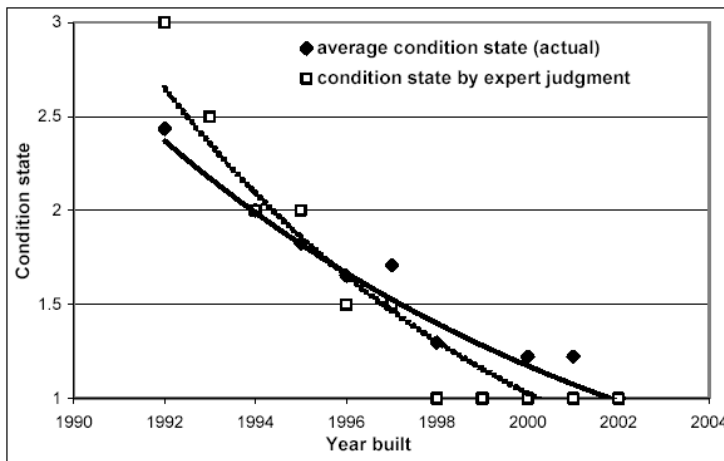


Figure 5. Deterioration of standard element 4200 “Close movement joint”

As visible from Table 1, experts’ judgment referring to “rated durability” for most SE was excessively pessimistic and corresponded to minimal values within the given life span obtained on the basis of inspection findings. Real longevity of SE on the Moscow bridges exceed the judgment almost twice (87% on average). An assessment of the durability using the “lower limit” criterion significantly affected the objectivity of the prediction in the process of the BMS operation.

In order to obtain a relatively reliable prediction, one should assign the parameters of fan-shaped deterioration model individually for each SE, considering its quality, as well as the mutual influence of adjacent elements.

This can be resolved by applying to each SE a specific rating coefficient equal to

$$\lambda_i = k_{qi} k_{infj} \lambda_{0i} \quad (9)$$

Table 1. Service life of some standard elements

Standard element	Age according to experts' years	Age according to the analysis findings, years	K_{var}	Type of deterioration model	
Concrete coating	10	29	0.00	Fan-shaped	
Butt-end of reinforced concrete girth rail	30	60	0.22		
Bearing block	40	59	0.19		
Embankment	75	98	0.03		
Steps	20	39	0.32		
Butt-end of reinforced concrete beam	30	58	0.23		
Butt-end of reinforced concrete slab	30	54	0.21		
Reinforced concrete stair flight	30	49	0.19		
Reinforced concrete cornice	30	55	0.26		
Reinforced concrete	60	90	0.23		
Reinforced concrete slab	60	110	0.31		
Reinforced concrete beam	80	133	0.12		
Reinforced concrete cross beam	80	127	0.06		
Steel	100	169	0.28		
Steel beam	100	184	0.22		
Steel column	100	188	0.34		
Steel cross beam	100	125	0.03		
Steel longitudinal beam	100	115	0.15		
Steel slab	100	132	0.13		
Gates	20	29	0.00		Zero
Door	20	34	0.18		
Reinforced concrete railings	30	67	0.13		
Closet wall	60	75	0.09		
Front of reinforced concrete slab	20	43	0.27		
Roof	60	69	0.06		
Architectural element	50	90	0.20		
Cast iron	100	151	0.14		
Antisplash guard	20	48	0.17		
Steel rigid barrier	30	44	0.00		
Parapet	20	35	0.29		
Sidewalk block	30	60	0.06		
Shield	50	64	0.12		
Plastic	30	61	0.10		
Service stairs	30	44	0.00	Stochastic	
Breccia	20	41	0.17		
Dry joint	60	81	0.01		
Hinged coating	30	48	0.30		
Barrier	20	43	0.29		
Reinforced concrete pedestal	20	35	0.37		
Frame	50	66	0.11		
Stone border	30	63	0.11		
Reinforced concrete lower slab	60	57	0.30		
Arch	80	117	0.13		Exponential
Sight cart	15	51	0.08		
Concrete	80	118	0.21		
Ceramics	20	32	0.20		
Wood	15	29	0.00		
Infill of joint	20	38	0.33		

Metallization	30	48	0.14
Paint coating	10	21	0.33
Protective coat	10	18	0.34
Plaster	10	19	0.33
Border	30	68	0.22
Concrete tile	20	40	0.32
Gutter	15	31	0.36
Slope gutter	25	69	0.06
Drain-pipe	20	28	0.23
Steel cornice	60	85	0.37
Reinforced concrete longitudinal beam	80	98	0.24
Wall of stair flight	60	92	0.36
Strengthening of slope	30	52	0.18
Facing (ceramics, marble)	30	55	0.25
Reinforced concrete girth rail	60	68	0.10
Concrete joint	80	109	0.15
Pre-stressed reinforced concrete	100	143	0.27
Steel shell	60	118	0.03
Stone cornice	60	150	0.08
Cast-iron railing	80	174	0.12
Reinforced concrete arch	80	113	0.26
Drainage	20	37	0.35
Pre-stressed slab	100	281	0.09

where λ_i = the rating coefficient for the i-th SE,

k_{qi} = the quality coefficient for the i-th SE,

$k_{inf,j}$ = the coefficient of the effect of the j-th SE,

λ_{0i} = the rating coefficient (stored in the BMS catalogue) for a given SE. It is assigned according to average service time as prescribed by the procedure of refining initial data based on the inspection results. In course of refining, the mean value of the rating coefficient for all mutuality of SE of the exact type assigned for the whole bridge network should be calculated.

The quality coefficient (k_{qi}) characterizes those individual properties of an element that affect its service lifespan. It is determined as a ratio of the actual residual lifespan, estimated on the basis of inspection findings, to the initially determined lifespan, stated in the catalogue of deterioration models:

$$k_{qi} = \frac{\lambda_{0i}}{\lambda_{real}} \quad \text{at } k_{inf,j}=1 \quad (10)$$

If the values of k_{qi} are beyond the range of the average statistical scatter, two possible alternatives are considered, i.e. an inspection error and the effect of the structural environment can be either positive (e.g., the effect of tiling on reinforced concrete elements) or negative (damaged waterproofing, failure of expansion joints, etc.).

If an inspection has been carried out with adequate quality, the element that has a none-zero effect should be identified and the effect coefficient for SE couple “j-i” should be introduced into the computational models. This coefficient can be calculated as follows:

$$k_{inf,j} = \frac{k_{qi}}{k_{q \text{ med}}} \quad (11)$$

where k_{qi} = the quality coefficient of a given element; and

$k_{q \text{ med}}$ = the average value of the quality coefficient of SE of the same type for a given bridge falling into the range of the average statistical scatter.

The quality coefficient may be used not only for considering specific properties of a given SE or objectivity of a given inspection but also as a criterion for prescribing certain repair actions, e.g., provision of protective coating or replacement of an element with a new one of better quality.

Conclusions

The following conclusions can be drawn from the analysis of the results of standard inspection:

1. Usually, experts' judgment provides underestimated prediction of the condition corresponding to the lower limit of the average statistical scatter of service lifespan. For most standard elements such an approach is not justified and leads to substantially erroneous results, which necessitates adjustments of parameters of the deterioration models in conformity with inspection findings.
2. Deterioration of bearing and frame structures of bridge facilities is attributable primarily to the wear of materials. Deterioration of strength properties virtually does not occur or is of accidental character.
3. The applicability of the general principles adopted worldwide for describing deterioration of bridge facilities and their components (standard elements) by a fair monotonic curve has not been substantiated by the findings of standard inspections carried out in the process of the operation of Moscow BMS. It is, therefore, suggested to use 4 types of deterioration models for the description of the whole set of SE: exponential, handfan, stochastic and "zero". Handfan model should be refined for each SE by taking into account their quality of manufacture and mutual influence within a specific structural environment. For this purpose, an SE should be characterized, in addition to its metric parameters, by its quality indicators. Also, a set of SE should be characterized by indicators of their mutual effects on each other. These parameters should be determined in each particular case on the basis of inspection findings.

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