Reliability Prediction of Utility Tunnel Structures during Operation

Andrew SHILIN
Prof., Dr., General Director, "Triada-Holding"
Marshal Zhukov Ave.6, bldg 2,
123308 Moscow, Russia, trhold@comail.ru

Alexei KIRILENKO
Dr., Head of Diagnostics Dpt.,"Triada-Holding"
Marshal Zhukov Ave. 6, bldg 2
123308 Moscow,Russia, trhold@comail.ru

Michail ZAITSEV
Dr., Chief Technologist, "Triada-Holding"
Marshal Zhukov Ave.6, bldg 2,
123308 Moscow, Russia, trhold@comail.ru

Igor ZOLOTAREV
Chief Specialist, "Triada-Holding"
Marshal Zhukov Ave. 6, bldg 2
123308 Moscow,Russia, trhold@comail.ru

Summary

The work continues our previous researches in the field of utility tunnel structures operational reliability. A method of probabilistic assessment of structural bearing capacity change in the course of operation has been introduced.

Key words: utility tunnels, reinforcement corrosion, failure, reliability, no-failure performance, prediction, bearing capacity, margin index, probability, categories of structural technical state.

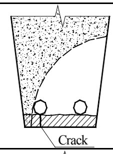
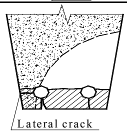
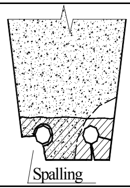
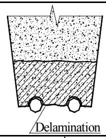
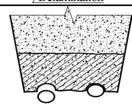
1. Introduction

One of the aspects of utility tunnels reliability prediction is the assessment of roof slabs service life with regard to accumulated defects and current loads. In our previous studies we used a statistic method of durability assessment based on the functional failure, i.e. loss of bearing capacity [1]. The process of defects accumulation was analyzed as the result of the influence of two aggressive factors: carbonization of concrete cover due to the action of tunnel environment and penetration of chlorides into the structural concrete from the surrounding ground as a result of defects in the tunnel outer waterproofing membrane. The sequence of defects accumulation (emergence and opening of cracks, concrete cover spalling) was correlated to reinforcement corrosion [2] which allowed to introduce categories of damages on the basis of the above-mentioned indications. It was further established that changes in the design bearing capacity of roof slabs (the weakest point in the whole tunnel structure) are mostly explained by reinforcement corrosion; the degree of corrosion propagation is assessed by the loss of bar diameter (in %) [3,4].
Repair works executed in due time allow to increase durability of structures and prevent their functional failure. To plan terms and types of repair works it is necessary to predict changes in structural state. The present work is devoted to the development of statistical method of structural state changes prediction throughout the whole period of structure operation up to the loss of its bearing capacity.

2. Initial Data for Modelling

Initial data for modelling is based on the results of inspection of more than 70 km of utility tunnels with various terms of operation as well as with different damages. A roof slab being the weakest point in the tunnel structure has been chosen as an object for modelling.
To assess the actual state of a structure a new classification that includes five categories of structural technical state has been introduced (Table 1). This classification takes into account both type of corrosion damage and limit of reinforcement corrosion (in %) for each category.

Table 1

Category of technical state	Description	Limit of reinforcement corrosion, %	Type of limit corrosion damage
I. Very good operational state	Meets the requirements of construction standards. No need of repair.	Up to 2	
II. Good operational state	Meets the requirements as to bearing capacity. Doesn't meet the requirements as to suitability for normal operation. Local loss of concrete protective function; corrosion protection should be restored.	From 2 up to 7	
III. Limited operational state	Meets the requirements as to bearing capacity to the limit level. Doesn't meet the requirements as to suitability for normal operation. Performance parameters should be restored.	From 7 up to 15	
IV. Inadmissible state	Doesn't meet the requirements. Temporary loads should be restricted. Bearing capacity should be restored. Local structural strengthening is required.	From 15 up to 25	
V. Breakdown state	Doesn't meet any requirements. Temporary loads should be immediately eliminated. Additional support and strengthening are urgently required.	More than 25	

The current state of roof slabs has been assessed by changes of their bearing capacity. Taking into account numerous variants of operational conditions realization the bearing capacity change was considered as the loss of bearing capacity margin (K_{sm}) described by the following relationship:

$$K_{sm} = \frac{M_0 - Mu(t)}{M_0 - M_D} \qquad (1)$$

where M_o is the bearing capacity of a roof slab at the initial moment; M_D is an externally applied moment; Mu(t) is the roof slab bearing capacity that changes in the course of operation. The value of Mu(t) depends mostly on the actual state of reinforcement cross-section and has a direct correlation with the corrosion damage of reinforcement. Using [3,4] we obtain:

$$Mu(t) = (1 - 0{,}01K)R_S A_S(t) h_0 (1 - \frac{R_S A_S(t)}{2R_b b h_0}) \qquad (2)$$

where R_s is reinforcement strength; $A_s(t)$ is reinforcement cross-section that changes in the course of operation; h_o is an effective height of design cross-section; R_b is concrete strength; b is slab width; K_c is reinforcement corrosion (%):

$$K_c = \frac{A_S(o) - A_S(t)}{A_S(o)} \cdot 100\% \qquad (3)$$

where $A_s(o)$ is initial reinforcement cross-section.

It should be noted that at the initial moment $Mu(t)=M_o$ and $K_{sm}=0$ which means that there is a full bearing capacity margin. If $Mu(t)=M_D$, then $K_{sm}=1$ which means that there is a complete loss of bearing capacity margin. Intermediate values ($0<K_{sm}<1$) determine the state of a structure during its operation according to this output parameter.

Equations (1), (2), (3) allow to make a comparative assessment of gradual loss of bearing capacity margin K_{sm} due to corrosion damage (corrosion degree K_c). It is evident that the values of K_{sm} and K_c have a probabilistic character as they are defined by random values correlation.

For interconnection of the parameters K_{sm} and K_c an intermediate relationship has been obtained:

$$K_{Sm} = K_c \frac{M_0}{M_0 - M_D} \qquad (4)$$

This correlation takes into account quantitative criteria of transition of structures from one category of structural technical state to the succeeding ones and illustrates clearly the process of gradual loss of initial bearing capacity margin.

3. Mathematical modelling

Based on the algorithm created by us earlier [1], the model has been further developed being designated to express numerically random values of parametric failures up to the functional one.

The research process included the following: imitation modelling, bringing together the data obtained and its grouping, determination of generalizing indices, analysis of results. Random arguments distribution data obtained in our previous [3,4] and latest researches has been used as initial data for modelling.

The period of modelling parameters calculations Δt has been assumed as 0,3 years. This is the minimum period for a parametric failure to reveal itself. For confidence level of 0,95 the necessary and sufficient quantity of tests (process realizations) P=600 has been defined.

Results of the modelling have been obtained with the help of Monte-Carlo method in accordance with the three main probabilistic parameters of the structures. They are presented in the form of bar graphs and cumulative distribution curves:

- changing of reinforcement corrosion in time – percentage of corrosion $K_c(t)$;
- decrease of structure bearing capacity margin depending on reinforcement corrosion $K_{sm}=f(K_c)$;
- decrease of structure bearing capacity margin in time $K_{sm}(t)$.

It should be noted that distribution of probabilities for the said parameters have been obtained for failure zones.

4. Results of modelling

The process of structural behaviour with regard to interconnection of all obtained probabilistic parameters can be presented as a volumetric figure limited by surfaces defiged by the confidence level of 0,95. Assuming that these surfaces are planes the results of modelling were grouped to establish boundary conditions for transition of structures from one category of technical state to the succeeding ones (corrosion degree 2, 7, 15, 25, 40%). The changing of probabilistic parameters is followed by dispersion of their values in relation to expectation. Certain realizations of the process have the character of monotone decrease. In this connection another assumption was introduced: the general population of realizations lies within the dispersion fields, the boundaries of which have been defined by our first assumption. Thus, in the sectional view of the volumetric figure there are plane quadrangles. The general solution then can be represented in a three-dimensional space as function $F=f(K_c, t, K_{sm})$ (Fig.1).
To present the analyzed stochastic process more clearly and to reveal probabilistic parameters relationship the general solution has been projected on the planes (K_{sm}; t), (K_c; t) and (K_c; K_{sm}), where three pairwise-dependent components of the process have been obtained. Depending on the set of random input parameter $K_c(t)$ they determine the law of formulation for the output parameter $K_{sm}(t)$ via random unit transition function $K_c=f(K_{sm})$.

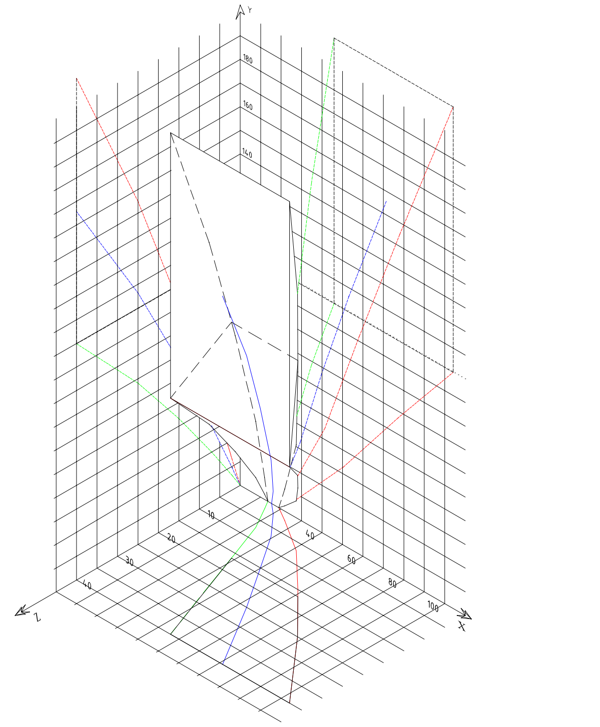


Fig.1. General solution for stochastic process of underground structure behaviour in the course of operation: x – term of operation T, years (10-year intervals); y – index of bearing capacity margin loss; z – reinforcement corrosion K_c, % (5% intervals)

According to the current standards, “no-failure” which is the property that determines reliability of any construction system both prior and after the repair – can be characterized by “no-failure” itself and the contrary characteristic, i.e. failure as they form the complete event only together. The first option - characteristic by “no-failure” - is more preferable as, on one hand, we can assess reliability immediately and directly and, on the other hand, modelling data can be processed easier. That’s why we can present the values of input/output parameters probability as well as the values of transition function in the range of system failure as obtained by modelling in the form of the opposite ones, i.e. by “no-failure”. The probability of occurrence of two dependent events (by “no-failure”) is determined by the rule of logical multiplication. Then we obtain the probability of margin index reduction in time $P(\overline{K_{Sm}(t)})$:

$$P(\overline{K_{Sm}(t)}) = P(\overline{K_c(t)}) \cdot P(\overline{K_{Sm}(K_c)} \mid \overline{K_c(t)}) \qquad (5)$$

where $\overline{K_{Sm}(t)} = 1 - K_{Sm}(t)$; $\overline{K_c(t)} = 1 - K_c(t)$; $\overline{K_{Sm}(K_c)} = 1 - K_{Sm}(K_c)$.

Using the relationship (5) to plot the isofields of equiprobability by “no-failure” for random values of output parameter $K_{sm}(t)$ depending on random corrosion process (input parameter $K_c(t)$) and random transition function $K_{sm}=f(K_c)$. The fields have been plotted for boundary conditions of transition of structures from one category of technical state to the succeeding ones with degree of corrosion 2, 7, 15, 25, 40% (Fig. 2).

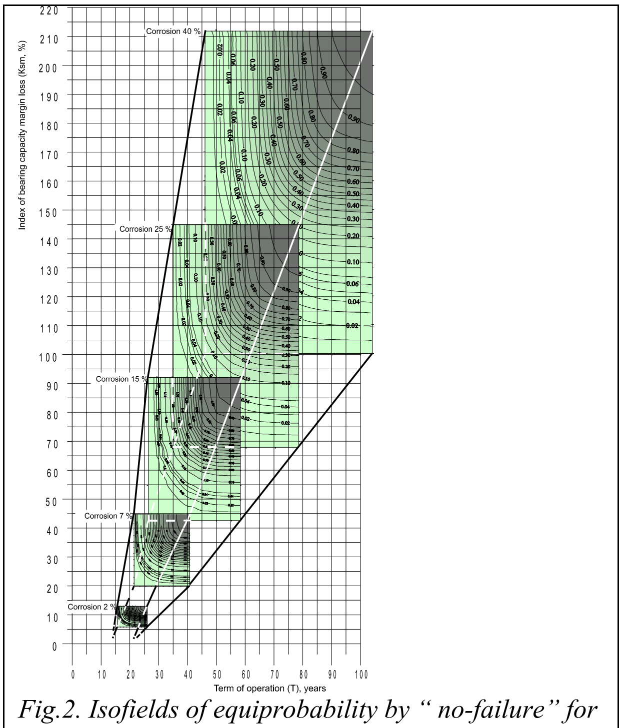


Fig.2. Isofields of equiprobability by “ no-failure” for random values of output parameter $K_{sm}(t)$

Reliability of the results obtained in the process of modelling has been confirmed by the results of inspections carried out in 9 utility tunnels with various terms of operation – from 19 to 42 years (inspection data hasn’t been used in the process of modelling). More than 500 roof slabs have been inspected in each tunnel. In the course of inspection the degree of corrosion-induced structural damage has been defined with ranking of the slabs into several categories of technical state. The results of prediction correspond to inspection data with the degree of reliability not less than 0,80. In accordance with the assessment of the current state and predicted behavior of roof slabs suitable maintenance strategy was proposed to the client. The repair works based on this strategy allowed to reduce drastically structural breakdown fund by optimum investments.

5. Conclusions

1. The probability prediction of utility tunnels reliability is based on the classification of their technical state and ranking into categories. It contains a multidirectional vector of stochastic parameters of corrosion-induced damage accumulation and takes into account the probabilistic character of external loads.
2. Three-dimensional probabilistic model of reliability developed by the authors can be used to predict damage in utility tunnel roof slabs in time. The model takes into account stochastic processes of damage accumulation and bearing capacity reduction in aggressive external/internal media as well as random character of current loads. Probability (by "no-failure") of random values of output parameter $P[K_{sm}(t)]$ are determined by multiplication of probabilities of input parameter $P[K_c (t)]$ by conditional probability of transition function values $P[K_{sm}| K_c]$.
3. To back up the strategy of utility tunnels operation at a certain level of reliability as well as to work out repair technology the probabilistic relationship mechanism of structural current state and changes in structural bearing capacity in time should be considered as the basic principle.

References

[1] Shilin A., KirilenkoA., Pavlov O. Service Life of Precast Reinforced Concrete Members in Urban Rectangular Tunnels with Regard to Corrosion of Reinforcement // *Proc. of the Int. Conf. On Corrosion and Corrosion Protection of Steel in Concrete.* - Sheffield, UK, vol.1, 1994, pp.638-647.

[2] Shilin A., KirilenkoA., Pavlov O. Repair in Utility Tunnels in Moscow. *Structural Faults + Repair - 99 // 8 Int. Conf. on Extending the Life of Bridges, Civil + Building Structures.* – UK, Univ. of Edinburgh, 1999, pp.231-232. CD.

[3] Shilin A., Shuplik M., Pavlov O., Kirilenko A. Life-Cycle Performance Prediction and dura bility Design for Urban Tunnel Structures // *Proc. of the RILEM/CIB/ISO Int. Symp. on Inte grated Life-Cycle Design of Materials and Structures.* - Helsinki, Finland: ILCDES 2000, May 2000, pp.497-501.

[4] Shilin A., Pavlov O., Kirilenko A. Reliability of Utility Tunnel Structures in Moscow // *Safety, Risk and Reliability - Trends in Engineering. Int. Conf.* - Malta, March 2001, pp.353-354. CD.