

# PREDICTION OF CONCRETE BRIDGE DETERIORATION CAUSED BY DE-ICING SALTS IN LATVIA

Kristaps Gode<sup>1</sup>, Ainārs Paeglītis<sup>2</sup>

<sup>1,2</sup>Rīga Technical University, Rīga, Latvia

<sup>1</sup>Āzenes iela 20, kristaps.gode@inzenierbuve.com

<sup>2</sup>Āzenes iela 20, ainars.paeglitis@rtu.lv

**Abstract.** When spread on the road de-icing salt or salt solution mixes with water and is splashed and sprayed by traffic onto concrete bridge structure surfaces. De-icing salts, which contain chlorides, initiate and accelerate the corrosion process of reinforcement within the concrete structure. The reinforcement corrosion is the most common cause of reinforced concrete bridge deterioration in Latvia. Since the bridges are one of the largest community investments and because of ever increasing maintenance and repair costs, it is important to improve durability of these structures, which could be achieved by better understanding of the processes and environment of chloride induced deteriorations. The chlorides penetrate the concrete cover, mostly by diffusion. Several bridge structures in Riga have been investigated in this study. The core samples were obtained from different surfaces and positions of the structures. The samples were examined for chloride content and chloride profiles were obtained. To perform service life calculation the theoretical chloride profile was fitted into the obtained chloride profile from the samples, and then diffusion parameters were calculated. The possible future profile was calculated for the target service life of 100 years. Chlorides from the de-icing salts spread on the roads are very unevenly distributed not only between different surfaces but also within one surface. The chloride profile shapes differentiate from the theoretical profile due to complex exposure conditions which feature constantly changing surface chloride concentration and moisture level. The chloride distribution depends on the form of the piers, position, distance from the road and the direction of traffic flow. Severe chloride exposure that can occur on high intensity roads for bridges with leaking expansion joints can significantly reduce service life of bridge structures that are built of good quality concrete and even have a concrete cover of 40 mm.

**Keywords.** Concrete bridges, service life, de-icing salts, chloride profiles, corrosion damage, road environment.

## INTRODUCTION

Design for durability of road infrastructures is becoming increasingly important in view of its large impact on economics. Reinforcement corrosion is the most common cause of concrete deterioration of bridge structures in Latvia. The ingress of chlorides is often considered to be the major threat to durability of concrete structures. During the winter season de-icing salts are spread out on roads to avoid formation of ice and ensure the anti-sliding properties of the road surface. The melting water mixes with de-icing salt and is splashed and sprayed on reinforced concrete pier structures by passing vehicles. Absorbed water with chloride ions initiates and accelerates the reinforcement corrosion process.

Roads with high traffic intensity require special care to maintain safe driving conditions during winter. During winter road maintenance regulations require the use of enormous amounts of de-icing salt. To prevent sliding of vehicles tires, the road authority has used the preventive method - spreading de-icing salts before ice buildup on the road surface during winter maintenance. To improve driving conditions during heavy snowfalls, de-icing salts are also used for fighting snow. This result is that bridge structures locate beside roadways with high-traffic intensity are highly exposed to intensive chloride ingress. Due to reinforcement corrosion caused by chlorides, the service life of bridge structures could be reduced to 40 years or less, though the Eurocodes define the bridge service life as up to 100 years. Since bridges are one of the largest community investments and because maintenance and repair costs will increase considerably, it is important to improve the durability of reinforced bridge structures by better understanding the processes and sequences of chloride induced deteriorations.

This paper describes the results of investigation performed on three reinforced concrete bridges near high-intensity traffic streets in Riga city and on the bridge located on Riga's bypass.

## 1 BACKGROUND

The service-life of concrete structures greatly depends on the durability of the materials used and the aggressiveness of the surrounding environment. Almost every type of deterioration mechanism of concrete structures can be modeled in a two-phase model with initiation and propagation phases

(Tutti, 1982). Chloride ingress is a part of the initiation phase while the reinforcement corrosion is part of the propagation phase. The chloride's penetration into the concrete cover layer can be modeled by the second Fick's law. A typical chloride ion profile consists of two different parts. The first part in depth  $\Delta x$  shows the decrease of chloride content close to surface where the chloride ions can be partly washed out by rain water during the summer period. This part forms the convection zone. The second part corresponds to Fick's law of diffusion (the diffusion zone).

For residual service life calculations can be used an empirical model (developed by DuraCrete project) which matches to Fick's law of diffusion and is easy to use for calculations (DuraCrete, Modeling of degradation, 1998), (DuraCrete, Final Report, 2000):

$$C(x, t) = C_i + (C_s - C_i) \cdot \operatorname{erf} \left( 1 - \frac{x}{2\sqrt{t \cdot D_{app}}} \right), \quad (1)$$

where:

$C(x, t)$	chloride amount in concrete depth $x$ (concrete surface, if $x = 0$ mm) and time $t$ [mass balance - %];
$C_i$	initial chloride concentration in concrete [mass balance - %];
$C_s$	surface chloride concentration [mass balance - %];
$x$	depth in concrete cover [mm];
$D_{app}$	apparent diffusion coefficient [ $mm^2/year$ ];
$t$	concrete structure age [years];
$\operatorname{erf}$	function: $\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-y^2} dy$ .

De-icing salt impact on concrete bridges in a road environment has been widely investigated in Sweden (Lindvall, 2003), (Fagerlund, G., 1996), (Fagerlund, G., 2005) where the climate is similar to Latvia. The obtained results allowed making these conclusions:

- Each bridge must be treated separately, because of the large chloride profile scatter.
- The chloride distribution greatly varies not only in-between different structures, but within one structure and even within one surface of the structure.
- Overall chloride profiles correspond very well to the previously described theoretical model.
- Convection zone depth varies greatly between profiles and varies from 10 to 25 mm.
- Chloride penetration is larger for surfaces close to the roadway (0 – 0.5m) and oriented towards the traffic (the splash exposure).
- Traffic speed does not have a significant influence for structures close to the roadway (splash zone), traffic speed might be important for structures that are located further away from the road (spray exposure).
- Large chloride penetration to columns has been observed at heights of 0 – 0.5 m above the ground level (the splash exposure).
- Chloride profiles for surfaces that are exposed to de-icing salt exposure depend on whether the surface is protected from direct rain or not. Surfaces that are unprotected from direct rain are more likely to have a longer service life than surfaces that are protected from rain.
- Diffusion coefficient values greatly depend on moisture levels of concrete cover.

Reinforcement corrosion caused by de-icing salt is also a major and common type of concrete bridge deterioration in other countries of the Baltic region (Kamaitis, Z., 2006).

## 2 DESCRIPTION OF THE INVESTIGATED BRIDGE STRUCTURES

### 2.1 Bridge piers of approach ramps to the Salu Bridge

Three approach ramp piers of complex of the Salu Bridge over the river Daugava in Riga have been investigated in this study. All three approach ramps have a similar structure and cross the same road not far from the city center. Investigated approach ramps were built in 1976 are numbered No.8, No.5 and No.7 (Fig.1). The piers are built in cast-in-place concrete (M300 with  $f_c = 125$  kg/cm<sup>2</sup>,

and frost resistance 200 cycles (Mp3-200) according to structural codes at the time). The design concrete cover depth according to the former Soviet codes was 30 mm for the main reinforcement. Piers are of rectangular shape with width 80 cm, length at the top 360 cm, at foundations 260-295 cm. Piers are located very close to the highway at different angles against the road axis.



**Fig. 1.** The right-side approach ramps complex of the Salu Bridge over the Daugava River.

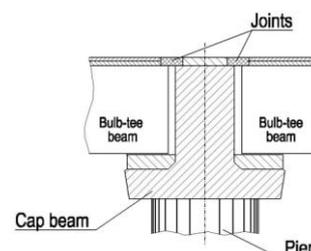
The highway beside the bridge piers has three lanes in each direction. The road surface has almost 4% inclination to the outside. Speed limit is 70 km/h and there is a high-traffic intensity volume over 20 000 vehicles/day. The bridge piers and other bridge structures are exposed directly to water containing chlorides that is splashed and sprayed by traffic for almost a half of the year.

## 2.2 Bridge over Bieķengrāvis

The bridge over Bieķengrāvis is situated on the left side of the river Daugava in the municipality of Riga and is part of the Salu Bridge complex (Fig.2). Bridge has six traffic lanes, speed limit of 70 km/h and traffic intensity of over 60,000 vehicles/ day. The bridge consists of 15 simply-based prestressed girder (bulb-tee beam) spans (concrete – M450 according to the former Soviet codes) and is 384.7 meters in length. This bridge was constructed in 1973.



**Fig. 2.** Bridge over Bieķengrāvis



**Fig. 3.** Support structure of the bridge

The bridge above each pier has two joints, which are the weak point of these type structures (Fig.3). Leaking joints may cause reinforcement corrosion damage to cap beam and tail-end parts of the prestressed bulb-tee beams.

## 2.3 Bridge over the Railroad – “Gaisa tilts”

This bridge is situated in municipality of Riga, where continuation of highway A2 enters the city center. The bridge has only two lanes of traffic and two tram lines, which can be used as a third traffic lane. The speed limit is 30 km/h and traffic intensity is over 35,000 vehicles a day. The three span bridge overpasses five railroad tracks. The superstructure and the middle span piers were built in 1963, whereas the masonry stone abutments were built in 1906. The side spans have 13.24 m long reinforced concrete T-beams (concrete M300); the middle span has 16.76 m prestressed concrete beams (concrete M400). The waterproof membrane beneath tram lines has been deteriorated and beams (especially side span beams) are exposed to moisture and de-icing salts.

## 2.4 Bridge over the Daugava on bypass – Highway A5

This bridge is situated on the Riga bypass highway A5. The bridge is located beside a hydro power plant “Rīgas HES” and has two lanes of traffic with intensity of over 10,000 vehicles a day. The bridge was built in 1973. The superstructure of the investigated bridge consists of six 24 meter long spans; each span has six prestressed concrete bulb-tee beams of 450 kg/cm<sup>2</sup> compressive strength at 28 days (concrete M400). Above each pier there is one expansion joint.

## 3 FIELD SURVEY AND COLLECTION OF SAMPLES

### 3.1 Bridge piers of approach ramps to the Salu Bridge

Core drilling was performed, and core samples were obtained from different pier surfaces and positions. Approach ramp No.8 pier is on the outside of highway with the widest surface facing towards traffic at a 31 degree angle. Reinforcement corrosion cracks were detected at the corner closest to the road (Fig.4). Core drilling was performed at 83 cm away from the corner and 33 cm above the ground surface. A second core sample was taken from another side of this surface (Fig.5).



**Fig. 4.** Reinforcement corrosion cracks at the pier corner.



**Fig. 5.** Core sampling from the ramp No.8 pier.

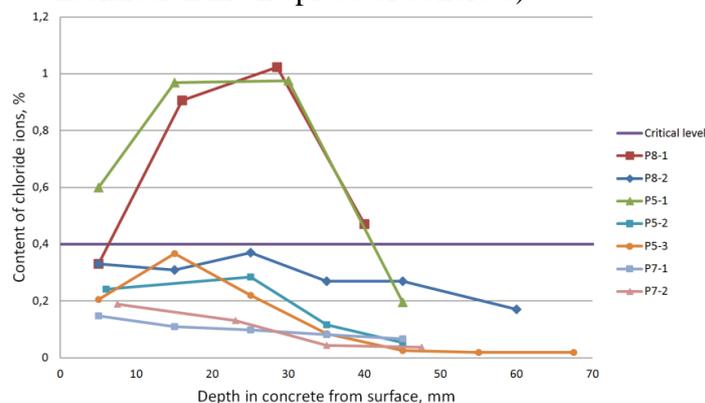


**Fig. 6.** Ramp No.5 pier and sampling location.

The pier of approach ramp No.5 is positioned close to the highway with the shortest surface facing towards traffic at 55 degree angle. This pier also had cracks in the nearest corner to the highway (Fig.6). One sample was taken from the surface facing traffic and three samples from the wide surface facing away from traffic. Sample No. P5-4 was taken for a pressure test of the concrete.

The pier of the approach ramp No.7 is positioned similarly to the pier of ramp No.5. The shortest surface faces towards traffic at a 64 degree angle. Two core samples were taken as follows: one from the surface facing toward traffic and one facing away from traffic.

The samples were cut at 10-15 mm intervals and the pieces were examined for chloride content (in compliance to EN 196-2 "Methods of testing cement. Chemical analysis of cement."). The amounts of chlorides in the concrete samples, are presented in the chloride profile shown in Figure 7 (one point describes chloride concentration in one piece of concrete).



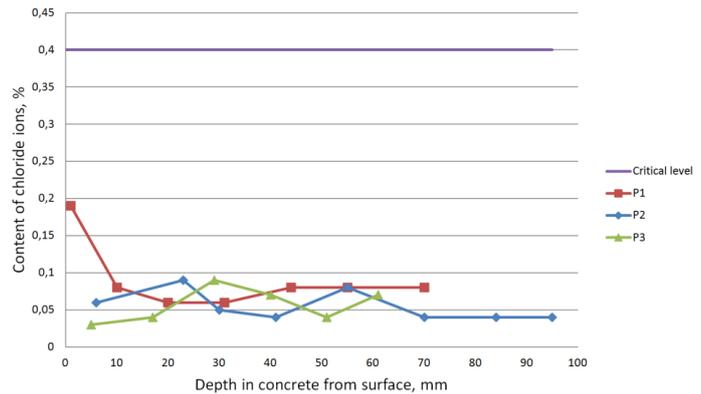
**Fig. 7.** Chlorides in cement paste of bridge piers.

### 3.2 Bridge over Bieķengrāvis

For the bridge over Bieķengrāvis we investigated corrosion initiated by de-icing salts that reach structure surfaces through leaking expansion joints. The core samples (Fig.8) were obtained from the web of the beam near the tail end of it (sample P2 and P3) and from the cap beam side surface bellow the leaching joint (sample P1). The chloride profiles from obtained samples are shown in Figure 9. The investigated web part of the beam did not have significant moisture signs. It was technically impossible to take the sample at very tail end of the beam, which might have a higher moisture exposure. The investigated cap beam surface that is located below expansion joint has been exposed to moisture and de-icing salts.



**Fig. 8.** Core sample from the web of the beam near leaking expansion joint



**Fig. 9.** Chloride profiles for the Bridge over Bieķengrāvis.

### 3.3 Bridge over the Railroad – “Gaisa tilts”

The bridge has deteriorated and also has leaking waterproof membrane beneath tram lines (Fig.11). During inspection it was stated that corrosion of reinforcement bars in the beams is developing, which is causing the concrete cover to crack and delaminate. Two samples for chloride investigation were obtained from the bottom part of the beam near reinforcements. This bridge also has leaking joints that cause chlorides to reach surfaces of the piers (Figure 10). During inspection severe corrosion of the bridge piers towards the bottom were noted. The third sample obtained from the bottom part of the pier showed very high chloride content (Table 1). It should be noted that the inspection took place at the end of the summer season where most of the chlorides from the surface were washed out.



**Fig. 10.** Corrosion of reinforcement.



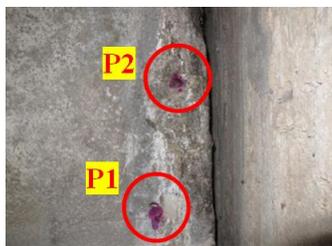
**Fig. 11.** Signs of leaking and deteriorated membrane.

**Table 1.** The chloride content of the bridge over the railroad (“Gaisa tilts”).

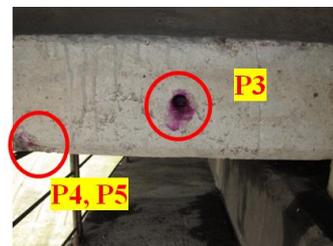
Sample	Position of the sample	Cl <sup>-</sup> , %
No.1	Span No.2-3, the bottom facet of the beam at pier No.3	0.41
No.2	Span No.2-3 the bottom facet of the beam at pier No.3	0.53
No.3	Pier No.1, from the bottom part at the depth of reinforcement	1.03

### 3.4 Bridge over the Daugava on bypass – Highway A5

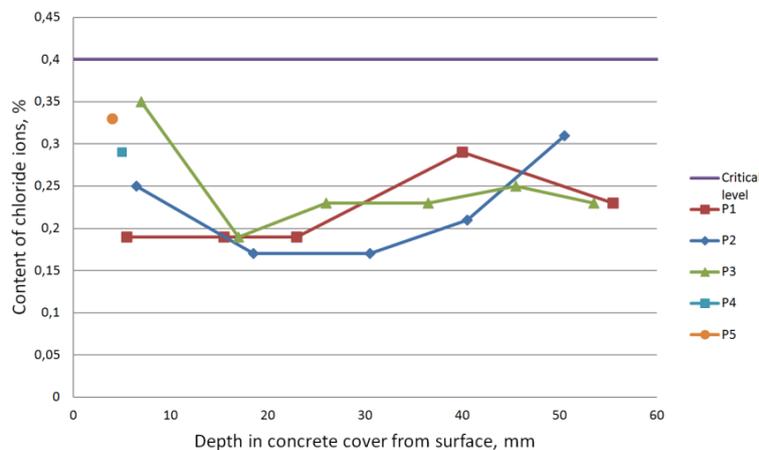
As this bridge has leaking expansion joints, samples P1 and P2 were obtained from the tail end of the beam near a leaking joint where moisture was obvious (Fig.12) and samples P3, P4, P5 from the position where no moisture or chlorides (signs) were present (Fig.13). Chloride profiles are shown in Figure 20. The inspection also took place at the end of the summer season where most of the chlorides from the surface were washed out. The samples were obtained by concrete drilling at different depths from the surface and collecting the concrete powder. The obtained chloride concentrations and chloride profiles are shown in Figure 14.



**Fig. 12.** Locations of samples P1 and P2 for Bridge over the Daugava on bypass A5.



**Fig. 13.** Locations of samples P3, P4 and P5 for Bridge over the Daugava on bypass A5.



**Fig. 14.** Chloride profiles for Bridge over the river Daugava on bypass A5.

## 4 DISCUSSION

### 4.1 Bridge piers located near the road

From Figure 14 we can see that the amounts of chlorides vary greatly at different depths in concrete and in different places of the structure. In depths under about 15 mm the chloride content is low. This shows that chlorides closer to the surface were washed out. The profiles with the highest chloride concentration (samples P8-1 and P5-1) were found from surfaces facing toward the traffic direction and closer to the corner of the pier. The profiles (P8-1 and P8-2) from the approach ramp No.8 piers were obtained from the same surface facing towards traffic. Profile P8-1 shows much greater chloride concentration, because it is much closer to the road. At the reinforcement depth 42

mm the chloride concentration is close to critical value of 0.4%. Since no corrosion was detected, it can be assumed that reinforcement corrosion threshold value is at least 0.4% or greater. Both profiles and the fact that there are reinforcement corrosion cracks at the pier corner, which is the closest to highway, show that chloride distribution is greatly influenced by the distance from the road and the angle at which the pier surface is facing traffic. Profile P5-1 was obtained from approach ramp No.5 pier's surface facing traffic, and is very similar to P8-1 profile. Other profiles from the surface facing away from the traffic show significantly less chloride concentration. Profile P5-2 which was obtained from the position a little lower than from profile P5-3 shows a bit more chloride concentration. The concrete cover depth of this surface was measured 60 mm. The profiles P7-1 and P7-2 were obtained from the both piers surfaces of the approach ramp No.7 facing towards and away from the traffic. Both show low levels of chloride concentration and cracks of reinforcement corrosion close to highway were not assessed. This convinces us that chloride concentration in the road environment is very variable.

#### **4.2 Leaking expansion joints**

The investigation shows that chloride levels are low for the bridge over Bieķengrāvis. The concentration of chlorides in the vertical surface of the cap beam show greater amounts in the top layer, but it is sufficiently low so as not to cause reinforcement corrosion in the foreseeable future. The concrete of the girder and cap beam are of very good quality. The chloride level in the bridge beam close to the leaking joint, but not directly exposed to chlorides, also is very low. The corrosion risk exists only for surfaces with direct chloride exposure, such as horizontal surfaces on the bottom part of the cap beam. Investigation showed that parts below leaking joints at several places have severe reinforcement corrosion. Chloride profiles for Riga bypass A5 Bridge over the Daugava show that in general the chloride concentration level is not high and will not initiate intensive primary reinforcement corrosion. Higher amounts of chlorides are found in depths to 10 mm. At depths of 10 – 60 mm, the chloride content is more or less constant and is not reducing, which means that the girders have relatively high initial chloride concentration, varying between 0.19% and 0.25%, on average 0.22%. This high chloride concentration could not accumulate during the service life (especially for sample P3), where the girders have not been exposed to intensive and long-term moisture influence. Chloride profiles for samples P1 and P2 show higher concentration at depths of 40 – 60 mm because the sample was obtained near the tail end surface of the girder (P1 – 12 cm and P2 – 6.5 cm from the tail end surface). Most likely these chlorides entered the concrete from the tail end surface which is situated right beneath the expansion joint. Visual inspection detected damage to the tail end surface of the girder, showing that there the chloride concentration is a lot higher and reinforcement corrosion is advancing. Reduced chloride amounts near the surface are likely to be washed out by water not containing chlorides during summer rains. Taking into account that girders have relatively high initial chloride concentration – on average 0.22% (usually it is about 0.1% (Lay, S., Schiessl, P., 2007)) the additional chloride needed to initiate corrosion should be a lot less. This means that these structures should not be exposed to de-icing salts for longer periods of time. In cases of expansion joint or waterproof membrane damages it would be necessary to stop applying de-icing salts and repair damage to prevent chlorides reaching girder surfaces.

#### **4.3 Leaking waterproof membrane**

The main reason for corrosion deterioration of the bridge over the railroad “Gaisa tilts” is leaking waterproof membrane and also leaking joints. The leaking membrane is below tram lines, which makes them difficult to repair and it is obvious that they have not been repaired for very long time. The leaking waterproof membrane causes girders to have a high moisture level throughout the year and chloride contained moisture during winter. Corrosion damage usually appears on the bottom

part of the beam and is spread within the whole span, which could cause the loss of structural bearing capacity in the middle of the span.

## 5 REMAINING SERVICE LIFE CALCULATIONS

Chloride profiles were analyzed to determine service life. To perform service life calculations, the theoretical chloride profile line was fitted into the obtained chloride profile from the samples, and by doing so diffusion parameters were calculated. Then the possible future profile was calculated for the target service life of 100 years. The calculation was performed using DuraCrete model as described previously at the deterministic and semi probabilistic level. Surface chloride concentration and diffusion coefficient were considered to be constant throughout the service life.

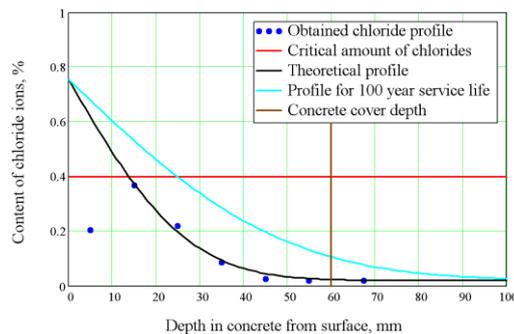
### 5.1 Bridge piers of approach ramps to the Salu Bridge

The profile P5-3 corresponds closely to the theoretical profile (Fig. 15). The future profile for 100 year service life is calculated by extrapolation. From figure 15 it can be seen that the critical concentration of chlorides at which corrosion may start has not reached the depth of reinforcement.

**Table 2. Results of diffusion coefficient calculations at deterministic level**

Profile	Number of useful points	Time in exposure, years	Surface chloride concentration, %	Diffusion coefficient, mm <sup>2</sup> /year
P8-1	2	33	-	-
P8-2	4	33	0.526	56.285
P5-1	2	33	-	-
P5-2	3	33	-	-
P5-3	6	33	0.756	7.384
P7-1	5	33	0.141	21.135
P7-2	4	33	0.236	14.217

Other profiles did not have sufficient points for reliable calculations or the chloride concentration is so low that it does not correspond to the theoretical chloride profile (table 2). Profiles 8-1 and 5-1 which showed greater chloride concentrations, have only 2 useful points for calculations, thus not providing reliable results.



**Fig. 15.** Calculation of chloride profiles (profile P5-3) at deterministic level.

### 5.2 Bridge over the Daugava on Riga bypass – Highway A5

For calculation of chloride ingress parameters and the remaining service life we used methodology from „Model Code for Service Life Design” (fib Bulletin 34, 2006) and (Lay, S., Schiessl, P., 2007). The calculations are performed at a semi-probabilistic level with reliability index  $\beta$  value of 1.8. In addition, the service life calculations were performed for a case of damaged and leaking waterproof membrane or expansion joints where high concentrations of chlorides reach superstructure surfaces.

The diffusion coefficient and surface chloride concentration were calculated using model (1).

The remaining service life was calculated using this equation:

$$\beta = \frac{\mu_{cover} - 2 \sqrt{t \cdot D_{app}} \cdot \operatorname{erf}\left(1 - \sqrt{\frac{C_{crit} - C_i}{C_s - C_i}}\right)}{\sqrt{\sigma_{cover}^2 + \left(0.5 \left[ 2 \sqrt{t \cdot D_{app}} \cdot \operatorname{erf}\left(1 - \sqrt{\frac{C_{crit} - C_i}{C_s - C_i}}\right) \right]^2}} \quad (2)$$

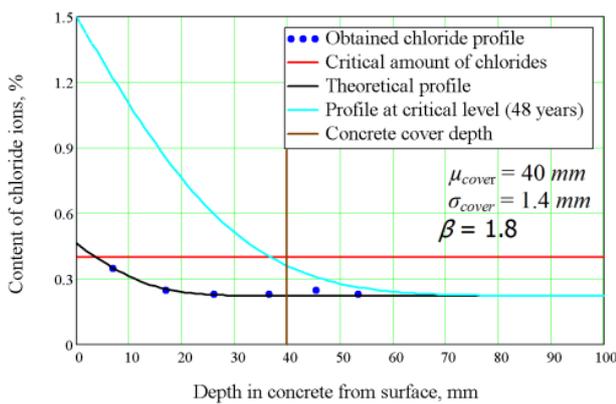
where:

- $\mu_{cover}$  mean value of concrete cover thickness [mm];
- $\sigma_{cover}$  standard deviation of concrete cover thickness [mm];
- $C_{crit}$  critical chloride concentration [mass balance - %];
- $\beta$  reliability index [-].

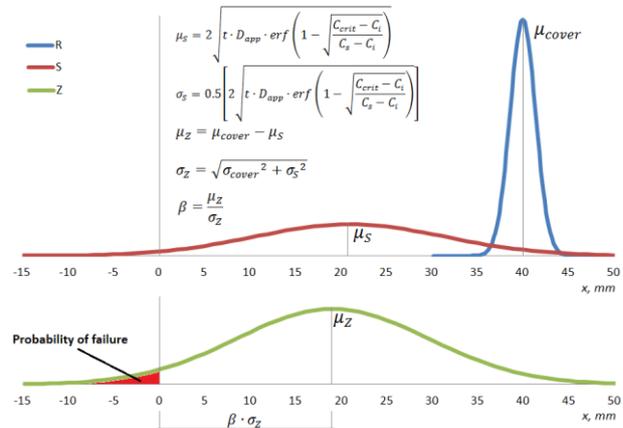
The input data and calculation results are shown in table 3 and figures 16 and 17.

**Table 3. Service life calculation parameters and results.**

Parameter	Current chloride exposure			Higher chloride exposure	
	9	20	40	20	40
Concrete cover, [mm]				20	40
Time in service, $t$ , [years]	10	10	10	10	10
$\beta$ , [-]	1.8	1.8	1.8	1.8	1.8
$C_{crit}$ , [%]	0.4	0.4	0.4	0.4	0.4
$C_i$ , [%]	0.22	0.22	0.22	0.22	0.22
$D_{app}$ , [mm <sup>2</sup> /year]	6.459	6.459	6.459	6.459	6.459
$C_s$ , [%]	0.461	0.461	0.461	1.5	1.5
$\mu_{cover}$ , [mm]	9	20	40	20	40
$\sigma_{cover}$ , [mm]	0.6	1.1	1.4	1.1	1.4
Remaining service life, $t_{remaining}$ , [years]	7	76	336	2	48



**Fig. 16.** Calculated chloride profile for 40 mm concrete cover in a case of a higher chloride exposure.



**Fig. 17.** Reliability concept for performed calculations.

## CONCLUSIONS

1. Chlorides from the de-icing salts spread on roads are very unevenly distributed not only between different surfaces but also within one surface. The chloride profile shapes differentiate from the theoretical profile most likely due to the lack of samples for one profile, but also due to complex exposure conditions which feature constantly changing surface chloride concentrations and moisture levels.

2. The results show that exposure to chlorides is generally highest for surfaces facing towards traffic and that are lower and closer to the road. The position and shape of the bridge piers are important.
3. Corrosion risk exists only for the surfaces with direct chloride exposure. Surfaces located below leaking waterproof membrane and expansion joints are exposed not only to de-icing salts but also a lot of moisture in summer that could reduce the chloride level in top layer of the concrete thus reducing the overall chloride amount in concrete.
4. Some older precast girder bridges might have a higher initial chloride concentration (above 0.20%), that could significantly reduce service life. The secondary reinforcement for structures built during the Soviet times is in danger of having corroding reinforcement even in lower chloride exposures.
5. Severe chloride exposure that can occur on high intensity roads for bridges with leaking expansion joints and waterproof membrane can significantly reduce service life of bridge structures that are built of good quality concrete and even have a concrete cover of 40 mm.

## REFERENCES

- Blomqvist, G. (1998). Impact of De-Icing Salt on Raodside Vegetation – A Literature Review. Linkoping, Sweden: Swedish National Road and Transport Research Institute.
- DuraCrete. (1998). Modeling of degradation. Gouda, The Netherlands: Brite Euram III Project BE95-1347, Report R4-6.
- DuraCrete. (2000). Final Report. Gouda, The Netherlands: Brite EuRam III Project BE95-1347, Report.
- Fagerlund, G. (1996). Livslängdsberäkningar för betonstruktioner. (Calculations of the service life of concrete structures). Overview with applications. Lund, Sweden: Lund Institute of Technology.
- Fagerlund, G. (2005). Long-term mapping of the chloride load around Swedish highway exposed to de-icing salt with reference to reinforcement corrosion in concrete. Lund, Sweden: Lund Institute of Technology.
- fib Bulletin 34. (2006). Model Code for Service Life Design. Lausanne, Switzerland: International Federation for Structural Concrete (fib).
- Kamaitis, Z. (2006). Deterioration of Bridge Deck Roadway Members. Part I: Site Investigations. The Baltic Journal of Road and Bridge Engineering, 1(4), 177-184.
- Kamaitis, Z. (2006). Deterioration of Bridge Deck Roadway Members. Part II: Condition Evaluation. The Baltic Journal of Road and Bridge Engineering, 1(4), 185-191.
- Lay, S., Schiessl, P. (2007). LIFECON: Service Life Models, Deliverable D3.2, Working Party 3. Munich: Tecnicl University Munich.
- Lindvall, A. (2003). Environmental actions and response - reinforced concrete structures exposed in road and marine environment. Goteborg, Sweden: Chalmers University of Technology.
- Tutti, K. (1982). Corrosion of steel in concrete. CBI research report 4:82. Stockholm: Swedish Cement and Concrete Research Institut.