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Impregnation of Concrete Bridge Elements Exposed to Severe Environment – Is It Cost Effective?

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Abstract

Concrete bridges located in marine environment or in cold regions with exposure to frequently repeated frost-thaw cycles and extensive use of de-icing agents need a good protection against these severe environments. To solve this problem, the codes prescribe dense concrete and thick concrete covers. On bridge elements that are especially exposed, the Swedish Road Administration also requires a surface protection, usually an impregnation of water repellent agents. Today, these systems have been used during more than two decades. From measurements taken it is known that they work properly, but what is not known is if they really are needed. In this paper, a Life-Cycle Cost (LCC) is conducted comparing cases where certain exposed bridge elements, e.g., the edge beams are either repaired and replaced when necessary or impregnated periodically. The results show that water repellent treatment is cost-effective on old concrete bridges.

Keywords: edge beams. life cycle cost, maintenance, repair, water repellent treatment.

1 Background

Swedish bridges and other outdoor civil engineering structures are exposed to a rather harsh environment since the country has a long coast line, many lakes, and a winter climate that demands a huge use of de-icing agents to maintain traffic safety. The use of de-icing salt is both important and effective at temperatures close to freezing (0°C). This is the condition in the most densely populated areas of Sweden. In the capital Stockholm, e.g., the number of temperature passages through 0°C may exceed 25 in only one single winter [1]. Hence, there is a need of various measures to warrant that any structure exposed to such environment has the necessary properties that it can fulfil all requirements during the intended service life. The measures comprise the use of high quality concrete, thick concrete cover, adequate design and detailing, suitable construction methods, a good workmanship, and a correct use of the structure including normal maintenance. In order to further improve the durability of concrete structures exposed to de-icing salts, water repellent treatments (WRT) have been used in Sweden since the 1980s [2]. According to the Swedish Road Administration [3], concrete surfaces in road environment with exception of the underside of the superstructure ought to be provided with WRT. Top sides, exterior sides, and undersides of edge beams are mentioned in a separate sentence. The research question is whether the WRT is a cost effective measure to prolong the service life of the concrete bridge or bridge element.

2 Life cycle costs

There are different ways of computing the life cycle cost of bridges or other structures. A simple and straightforward method is to compute the present value of all costs, i.e., at least construction costs, repair costs, and maintenance costs (including inspection costs). In a more sophisticated analysis, other costs may be included, e.g., failure costs, the road-users' costs, costs for traffic accidents, environmental costs, and costs connected to dismantling and depositing or recycling the structure. From the total cost, sometimes the estimated economic benefit of the bridge is subtracted. However, in this study it is considered that the construction cost is equal in all maintenance and repair alternatives and that the differences in all other costs and benefits, except the maintenance and repair costs, are negligible. Of course, this is not true, but for the scope of the comparison it has been considered to be sufficiently adequate.

Hence, the total repair and maintenance cost C may be computed by the following equation:

$$C = \sum_i \frac{C_{1,i}}{(1+p)^{mi_i}} + \sum_j \frac{C_{2,j}}{(1+p)^{mj}} + \sum_k \frac{C_{3,k}}{(1+p)^{mk}} + \dots \quad (1)$$

Where, $C_{1,i}$ is the cost for maintenance or repair action No. 1 at the *i*th occasion, *mi* is the age of the bridge at this occasion, $C_{2,j}$ and *mj* are corresponding values for action No. 2 at the j^{th} occasion, etc., and *p* is the interest rate.

3 Concrete deterioration

The concrete bridge element may be subjected to a number of deterioration mechanisms, e.g., reinforcement corrosion due to chloride ingress or carbonation, frost, acid action, or alkali silica reactions. For concrete bridges exposed to de-icing salts or marine climate, the predominant deterioration mechanism is reinforcement corrosion due to chloride ingress that may finally jeopardize the load-carrying capacity due to concrete cover spalling and reinforcement anchorage failure.

The corrosion process is usually considered to consist of two phases; (i) initiation and (ii) propagation (Figure 1). According to [5], increasing temperature (*T)*, relative humidity (*RH)*, and oxygen (O_2) content lead to an increasing corrosion rate during the propagation phase, however, for *RH* and O_2 this increase only continues to certain limits. For *RH*, the corrosion rate has its maximum at 96 %. In conservative service life design, the propagation phase is neglected. Hence, the service life is considered ended when propagation starts. For corrosion due to chloride ingress, this phase is obtained when the chloride content at the reinforcement level equals the chloride threshold value.

Most equations for determining the chloride ingress are based on Fick's second law and its solution for an infinite half-space. In its simplest form it reads as follows:

$$c(x,t) = c_0 \cdot \left(1 - \operatorname{erf} \frac{x}{2 \cdot \sqrt{D \cdot t}}\right) \quad (2)$$

Where, $c(x,t)$ = chloride content at time *t* and distance *x* from the exposed surface, c_0 = chloride content at the exposed concrete surface, *D* = chloride migration coefficient, and erf = the so called error function. Corrosion starts when $c = c_{threshold}$ at *x* = concrete cover. Both c_0 and $c_{threshold}$ are on one hand difficult but on the other hand not necessary to estimate, since the focus is on the structure of the equation. By analysing the argument $x/\left(2 \cdot \sqrt{D \cdot t}\right)$, it may be concluded that if the distance *x* is doubled (to 2*x*), the same chloride content is obtained at the fourfold time

(4*t*). Similarly, doubling the *D* value implies that the time is reduced to 50 percent.

Therefore, the study focuses on the reinforcement corrosion due to chloride ingress while the corrosion propagation is neglected.

Mattsson et al. [4] investigated concrete edge beams on Swedish bridges. During 15 years from 1990 to 2005, 135 edge beams were replaced and another 125 ones were repaired in the region around the Mälaren lake. The authors found that on average, edge beams were repaired after 28 years and replaced after 45 years. The standard deviation was 15 and 11 years, respectively. This reflects more the condition of historical bridges than beams on bridges constructed today. Since the durability of concrete has been highlighted in recent years and the demands on concrete quality and concrete cover have been sharpened, it may be anticipated that brand new concrete edge beams will perform well during a significantly longer period than 45 years. However, with increasing traffic, probable climate change, and the uncertain future use of de-icing agents, the circumstances may be completely different than today, any service life estimation is uncertain.

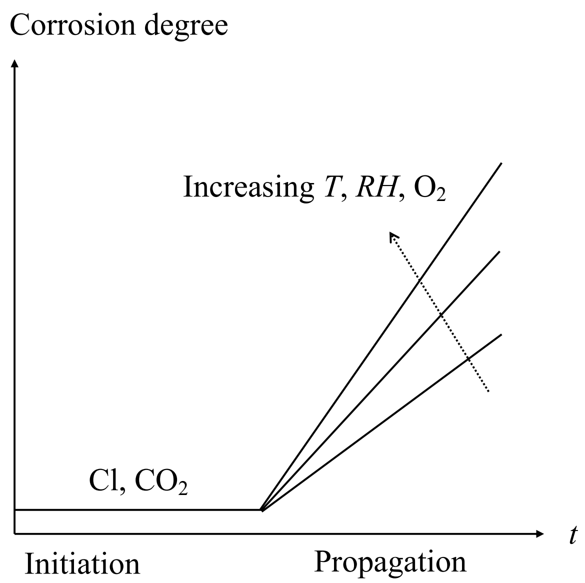

Figure 1: Schematic representation of the corrosion process according to Tuutti [5].

4 Surface protection using WRT

Both laboratory tests and field measurements show that a water repellent treatment (WRT) is an effective method to improve the durability of concrete. Both the chloride ingress rate and the moisture content diminish. The reduced moisture content implies that the frost damage risk is reduced and that the circumstances for corrosion are less crucial. The corrosion rate diminishes markedly when the relative humidity, *RH,* diminishes below 97 % [5]. Consequently, both the corrosion initiation and the corrosion propagation periods are prolonged. As mentioned, this study focuses solely on the initiation phase.

Several research reports, e.g., [6-8], show that the chloride migration coefficient and the moisture diffusion coefficient decrease if the concrete surface is treated with water repellent agents. Since the chloride ingress mainly is a diffusion process, there is a certain relationship between the two coefficients investigated. However, for the scope of this study it is not necessary to make clear the nature of this relationship. It is more interesting to compare treated and untreated concrete. Olsson & Sjödin [6] studied the effect of WRT on moisture profile, chloride ingress, and frost durability in self compacting concrete. They tested two concrete mixes. The water repellent agent was applied as a liquid or as a cream after 28 days. The chloride migration coefficient was tested according to NT Build 492-99 [9] starting at a concrete age of 48 days.

Liu et al. [7] tested a concrete mix with w/c = 0.45 intended for marine exposure. The specimens were stored in four different climate conditions during six weeks. For the purpose of this paper the climate condition given by T = 20°C and RH = 100 % was considered to be the most interesting.

Johansson et al. [8] determined the moisture diffusion coefficient by measuring the moisture flow through untreated and treated concrete samples of two concrete mixes at four different relative moisture levels and interpreting the results by using Kirchhoff's flow potential. Thus, the moisture diffusion coefficient can be estimated at an arbitrary RH. For the current comparison, the value at RH = 90 % was selected.

The results from the three investigations are summarized in Table 1. It can be observed that the WRT reduces the coefficient markedly at high w/c ratios and slightly at low w/c ratios. Since concrete structures in harsh environments usually are cast with high concrete qualities (low w/c), the benefit of the WRT might be quite small, how small will be determined in Section 6.

Table 1: Some measurements on chloride migration coefficient or moisture diffusion coefficient on untreated and treated concrete

w/c ratio	*RH*	D_u (m^2/s) for untreated concrete	D_t (m^2/s) for treated concrete	D_t/D_u	Reference
0.70	NT Build 492-99	$32.4 \cdot 10^{-12}$	$11.2 \cdot 10^{-12}$	0.35	Olsson & Sjödin [6]
0.40	NT Build 492-99	$10.4 \cdot 10^{-12}$	$9.7 \cdot 10^{-12}$	0.93	
0.45	100	$6.10 \cdot 10^{-12}$	$4.42 \cdot 10^{-12}$	0.72	Liu et al. [7]
0.80	90	$0.85 \cdot 10^{-6}$	$0.2 \cdot 10^{-6}$	0.24	Johansson et al. [8]
0.45	90	$0.50 \cdot 10^{-6}$	$0.2 \cdot 10^{-6}$	0.40	

In a recent field study, Johansson et al. [10] have shown that WRT can still be effective in protecting concrete from moisture transport after 15 years. Consequently, we may conclude that the concrete surface does not need to be retreated more frequently than every 15th year, maybe even more seldom.

5 Maintenance and repair strategies

In Sweden, there has been a trend indicating that the preventive bridge maintenance increases compared to corrective maintenance and repair. In 2002, the share of preventive bridge maintenance was estimated at 15 % [11]. A conscious maintenance and repair strategy consists of inspections, preventive maintenance measures, and repair actions at regular intervals. Some bridge elements may be designed with such durability that they do not need to be repaired during the entire service life while others might need both one and two repairs or replacement. The substructure is an example of the first and the edge beam is an example of the second kind.

For edge beams, any of the following strategies may be selected:

1. Construction – minor repair – replacement
2. Construction – major repair – replacement
3. Construction – replacement
4. Construction – WRT – replacement

All strategies include maintenance actions like cleaning after the end of the de-icing period and regular inspections. The listed actions may be repeated and under certain conditions the replacement might not be necessary. However, the four alternatives are selected for clearness and simplicity.

For various repair and maintenance actions, the Swedish Road Administration has listed unit prices that can be used to estimate the cost. In Table 2, the costs for minor repair, major repair, WRT, and exchange of edge beams are listed. The difference between minor and major repair is the estimated thickness of concrete removal and concrete replacement.

Table 2: Unit prices for various maintenance and repair actions for edge beams according to [12]

Description	Unit	Edge beam length to be maintained or repaired				
	m	0 – 99	99.1 – 199	199.1 – 299	299.1 – 499	> 499.1
Concrete repair 0-30 mm	SEK/m^2	2800	2300	2300	2000	2000
Concrete repair 30-70 mm	SEK/m^2	5000	3400	3400	3100	3100
WRT	SEK/m	230	200	200	200	190
Exchange	SEK/m	7000	6200	5500	5500	5500

Note 100 SEK = 10.54 € (Jan. 24, 2008).

6 Computation examples

The life cycle costs for various maintenance and repair strategies for a concrete edge beam exposed to de-icing agents have been investigated. The following assumptions are given:

- The edge beam has such a geometry that the relative surface is 1 m^2/m edge beam;
- The length of the edge beam is less than 99 m;
- The selected repair method is so efficient that the repaired edge beam has the same durability or remaining service life as the virgin edge beam (at traffic opening). This means that if the untreated edge beam has to be replaced after 45 years, then the replacement of the repaired beam can be postponed to 45 years after the repair. The assumption is valid for both minor (thin) and major (deep) repair;

- During repair only deteriorated or contaminated parts are removed and replaced. The amount of surface repaired depends on the original scatter in concrete properties or scatter in the local exposure conditions;
- The age at minor and major repair, respectively, has been assumed to reflect the large scatter (standard deviation = 15 years) in Mattsson's data [4] for edge beam repair. This way the average age at repair has been reduced for minor repair and increased for major repair. Thus, it is possible to discern the effects between minor and major repairs;
- If the edge beam is replaced, the durability of the replacement beam is assumed to be 90 years. The assumption is based on values of concrete quality and concrete cover that currently are used on Swedish concrete bridge elements. The standard target value is 120 years but 90 years are selected for conservative reasons;
- Two concrete mixes are investigated: (i) a concrete mix considered to represent concrete used on old bridges and (ii) a concrete mix used today for concrete edge beams in Sweden. However, for the aim of the study, the concrete mix has a minor importance. More interesting is that the time for chloride ingress is assumed to be 45 years in the old edge beams and 90 years in edge beams cast today. This prolonged service life is also considered to take the increased demands of concrete cover into account. The assumed difference in service life is likely to be underestimated, however, it was selected to make the comparison meaningful. Furthermore, even today edge beams are cast with uneven concrete quality, erroneous concrete cover, and insufficient curing.

Table 3: Input to the computation example

	Unit	Example A		Example B	
		Default value	Interval of investigated values	Default value	Interval of investigated values
Concrete type		Old		New	
w/c	-	0.60		0.40	
D_t/D_u	-	0.50	0.30 – 0.70	0.80	0.50 – 0.90
WRT interval	Years	15		15	15 – 35
Age at minor repair	Years	23		46	
Age at major repair	Years	33		66	
Age at 1st replacement	Years	45		90	
Percentage of repaired area at minor repair	Years	30	30 – 100	30	
Percentage of repaired area at major repair	%	100		100	
WRT cost	SEK/m	230		230	
Minor repair cost	SEK/m	2800		2800	
Major repair cost	SEK/m	5000		5000	
Replacement cost	SEK/m	7000		7000	
Interest rate	%	3	0 – 10	3	

The maintenance and repair cost development for the four selected strategies are shown graphically in Figure 2.

Not surprisingly, the interest rate *p* is of highest importance for the result. If the interest increases, the present values of measures taken late become smaller and smaller. For Example A, a zero maintenance and late replacement of the edge beam is most economic for cases with high interest rate (Figure 3). For normal values of *p* ($1 < p < 5$ %), WRT is the most cost-effective maintenance and repair strategy.

In the computations, it has been assumed that the chloride migration coefficient is reduced by 50 % when the old concrete edge beams are provided with WRT. The importance of this assumption has been investigated in Figure 4. Here, also the amount of surface that need minor repair has been studied. If only small areas need repair, this strategy seems to be competitive.

For new concrete bridges, the WRT is less competitive (Figure 5). This is due to the fact that new concrete bridges are cast with durable concrete and thick concrete covers. The WRT has to reduce the chloride migration coefficient at least by 25 %. Furthermore, the interval between WRT actions has to be prolonged to more than 20 years to make this treatment cost-effective. In other cases, it is more cost-effective to save the costs of WRT and replace the edge beam when its condition finally is too poor. Minor repair seems in this case to be the most cost-effective maintenance and repair strategy.

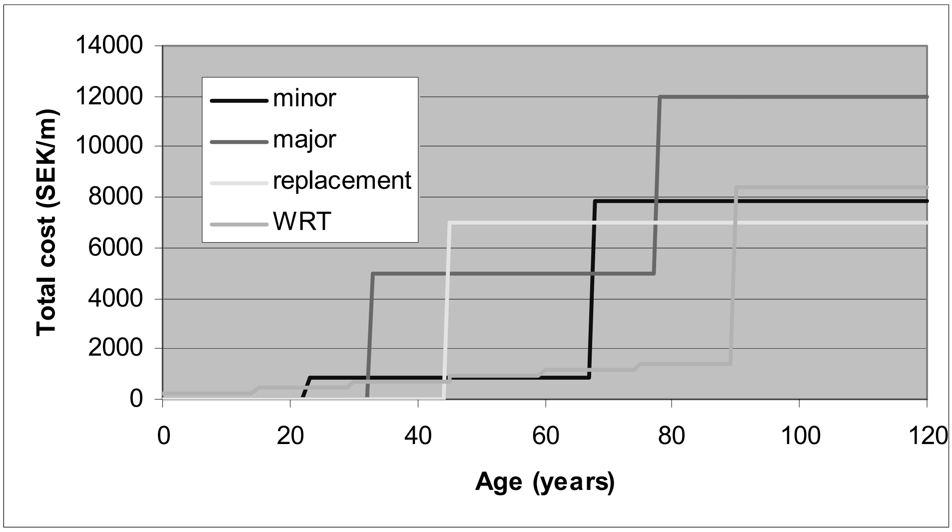

Figure 2: Maintenance and repair cost development for the four strategies and an interest rate $p = 0$. Example A – old concrete edge beam.

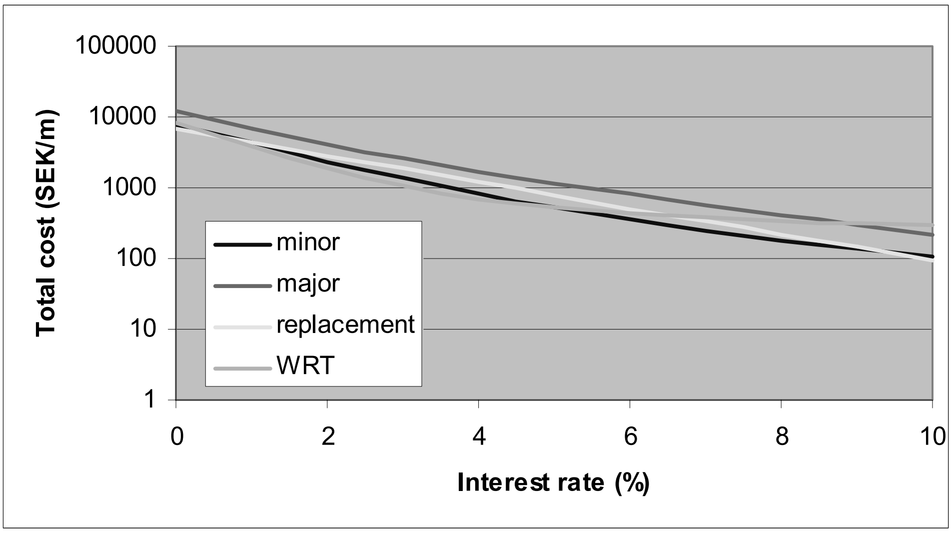

Figure 3: Total maintenance and repair costs during 120 years for varying values of the interest rate. Example A – old concrete edge beam.

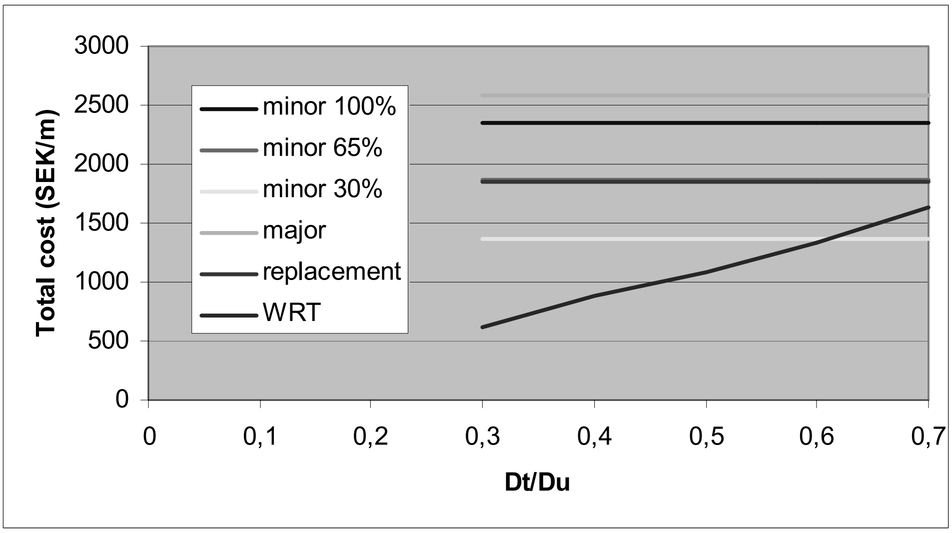

Figure 4: Total maintenance and repair costs for varying values on the chloride migration coefficient and different values of area percentage in need of minor repair. Example A – old concrete edge beam.

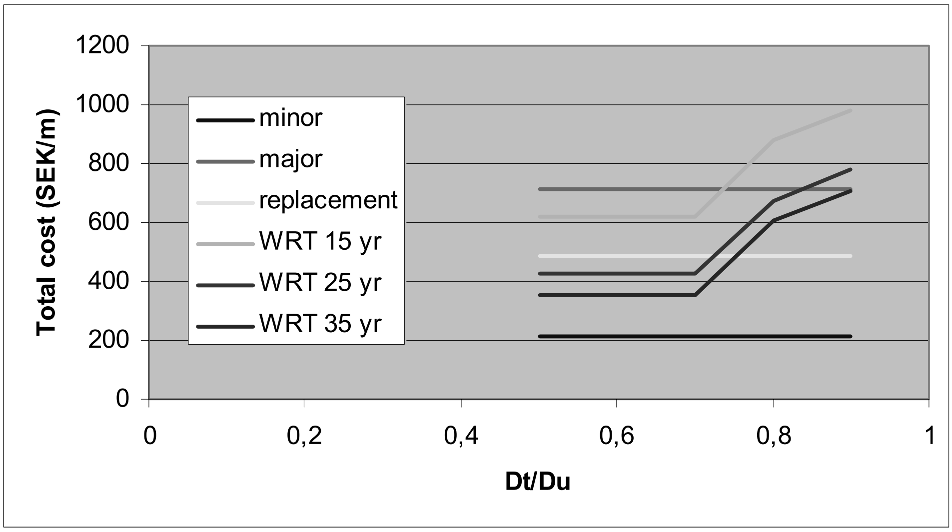

Figure 5: Total maintenance and repair costs for varying values on the chloride migration coefficient and varying intervals between the WRT. Example B – new-cast concrete edge beam.

7 Concluding remarks

In order to investigate the economic benefit of water repellent treatment, comparison LCC computations have been conducted for four different maintenance and repair strategies for concrete edge beams. The computation results are dependent on the selected input, but LCC analysis is an important tool in order to find the most cost-effective strategy. Particularly the assumed interest rate p has an important influence on the result. In the case of high values of p, it is difficult to motivate any continuous corrective maintenance, since the final replacement will have such a low present value. On the other hand, most highway agencies use low p values, and for these cases the WRT is often cost-effective.

This specific investigation shows that WRT is cost-effective on old bridges with normal w/c ratios whereas it is less cost-effective on modern concrete structures cast with low w/c ratios and provided with thick concrete covers. However, the results are dependent on the ratio between the chloride migration coefficients for treated and untreated concrete (Dt/Du). For dense concrete, this ratio was found to be fairly close to unity. However, the values used were based on a rather limited literature survey. If other tests show higher effectiveness the WRT would be more cost-effective also on modern concrete bridges.

A future development of this LCC would contain probabilistic methods in order to take the scatter of the various parameters into account.

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