RISK MANAGEMENT OF CONCRETE ROAD BRIDGES SUBJECT TO DE-ICING SALTS AND THE POSSIBLE IMPLICATIONS OF CLIMATE CHANGE

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ABSTRACT

Chloride induced corrosion from de-icing salts is the main cause of deterioration to reinforced concrete bridges in the UK. Climate change leading to warmer and wetter winters in the UK could increase corrosion rates in the future.

This paper considers the role of bridge inspection, monitoring, and corrosion protection measures in managing the risk of corrosion.

In the UK road bridges are inspected using set cycles of General and Principal Inspections. These are used to calculate a Bridge Condition Score from which the condition of a bridge can be monitored. The application of risk-based inspection regimes is considered and the use of new monitoring technology as part of the inspection processes.

Methods of reducing the risk of corrosion are considered, such as cathodic protection, reducing chloride de-icer use, and appropriate bridge design.

Improved methods of monitoring and corrosion protection according to risk can help to manage deterioration to optimise the operational life of structures. With the potential for corrosion rates to increase due to changing climatic conditions introducing uncertainties, it is becoming even more important for bridge condition to be monitored to enable repairs to be programmed over the life of the asset in the most cost effective manner.

1. INTRODUCTION

Reinforced concrete bridges are a key part of the transport infrastructure in the UK. From the Interim Report to the Association of Directors of Environment, Economy, Planning and Transport (ADEPT) National Bridges Group on the National Survey for Bridge Condition Indicators in 2011 [1] some 31.5% of all local authority bridges are of concrete construction, from a sample of 43623. By deck area the figure is even larger – 35.5% are of concrete construction with the next largest category by area being masonry with a figure of 13.9%.

Discounting the unknown bridge material data returns, the concrete figure is even more emphatic at 55.8%.

According to BA 35/90 (Highways Agency, 1990) [2], the most serious cause of deterioration of the Department of Transport's (DfT) concrete highway structures is reinforcement corrosion due to the presence of free chloride ions in the concrete. These mainly come from de-icing salt certainly away from the coastal areas.

Carbon steel reinforcement in concrete is maintained in a passive state by the highly alkaline environment that is normally present within cement-based materials. However, this passive state can be, and often is, disrupted leading to reinforcement corrosion.

Corrosion of steel reinforcement in concrete is only one form of metallic corrosion but it is the single largest cause of deterioration of our road infrastructure. The two primary causes of such deterioration are carbonation, which leads to the loss of concrete alkalinity and chloride ingress primarily from de-icing agents, which break down the protective oxide film of the steel reinforcement. The presence of moisture and oxygen can cause expansive corrosion. The volume occupied by the corrosion product can be up to eight times greater than the original steel product and the expansive forces are sufficient to cause concrete cracking, delamination and eventually spalling.

Winter service treatments for roads and bridges will generally use a chemical compound for both the prevention of ice forming and for the remedial treatment of ice that has formed or snow that has settled. Generically referred to as a de-icer the most common compound used is sodium chloride salt. For reasons of economy and practicality most road bridges will have de-icer applied as part of the overall road route operation using lorry mounted spreading equipment, generally spreading sodium chloride as the de-icer.

Sodium chloride is the most widely used de-icer on roads due to it being relatively cheap and readily available; however it has some fairly important limitations and disadvantages. When spread salt needs to go into solution to be effective as a de-icer. At temperatures lower than -5 to -7^{o}C (depending on humidity) salt will not go into solution rapidly enough to be effective in practical terms. At temperatures below -15^{o}C salt is not considered an effective de-icer as the solutions formed in actual road conditions are far from saturated. If saturated solutions are delivered (as brine) the solution will reduce in strength as ice or snow is dissolved, adding further water.

Climate change leading to warmer wetter winters in the UK could increase corrosion rates in the future posing a significant risk to concrete structures. This paper looks to expand and assess ways in which this risk can be better managed or even mitigated.

2. THE EFFECT AND / IMPACT OF CLIMATE CHANGE ON CORROSION RATE

Corrosion processes generally are complex, the rate of which depends on many factors such as the type of materials, geometry, condition and environment. Two key environmental factors are the prevailing climate and the presence of contaminants. High relative humidity, temperature and moisture levels at the metal surface increase the corrosion rate, and contaminants can draw moisture to the metal surface and increase the conductivity of the moisture. One of the main contaminants for road bridges is chlorides, mainly from de-icing salts. The quantity of de-icer and frequency of application depends on the severity of the winter, and the amount of precipitation, as re-application may be required when weather conditions change or rainfall removes the salt. Therefore, climate has a strong influence on corrosion rates, and a change in climate could have implications on the rate of deterioration of concrete bridges.

2.1. Potential climate change impacts

The Meteorological Office records show that the annual average temperature of the UK is increasing [3] and is projected to continue increasing at an advancing rate [4], see figure 1. Winters are expected to become warmer and wetter, conditions that could accelerate corrosion both directly and indirectly. Higher temperature increases the rate of the electrochemical reaction and diffusion, and increased rainfall and the number of wet days means there is more moisture available to drive the reaction. Relative humidity is projected to decrease in summer, and change little during winter, which may help to offset the anticipated increasing corrosion rates. Given that salt is likely to continue to be present then a warmer and wetter climate is expected to increase corrosion rates from present values.

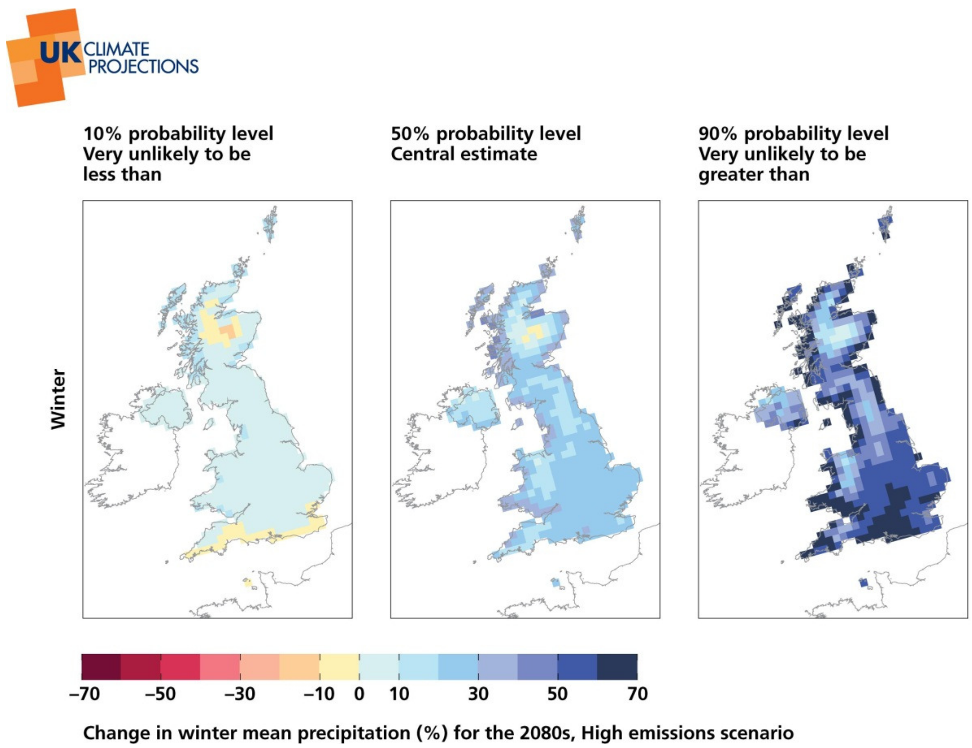

Figure 1 - Change in winter precipitation (© UK Climate Projections, 2009)

Warmer winters may mean less frequent de-icer application. However, wetter weather may result in more frequent re-application on the occasions when temperatures are low. It is unclear which of these will be the overriding effect. A French study [5] suggests there will be a decrease of winter service activities of 50% by 2100; however this is based on frost indices, so does not include the impact of precipitation on re-application. It should be noted that heavy rainfall can also remove contaminants for example salt deposited by traffic spray reducing salt levels.

There has been some research [6, 7], suggesting that the melting sea ice in the Arctic is influencing atmospheric circulation patterns in the Atlantic, introducing the possibility of more severe winters for the UK in the next 40-50 years, before returning to the trend of warmer winters. If there are more severe winters in the short term, de-icer use may increase during this time. However this is just one of many climate factors influencing UK winter temperatures and is an area of on-going research.

Although, weather is the largest influence on de-icer use, many other factors such as changes in policy, public pressure and new technologies and techniques such as pre-wet salt influence the amount and frequency of de-icer spread. Latest trends, even allowing recent severe winters, demonstrate increasing de-icer use.

2.2. Understanding the changing influences on corrosion rates

The different climate influences on corrosion are not fully understood and to-date limited work has been carried out on the impact of climate change on corrosion rates. A study combining existing corrosion models and climate projections for Australia [8] suggests the impacts could be site specific. From 1990 to 2100, a 14% increase in steel corrosion rates was found for Brisbane and a 14% decrease for Melbourne. The calculations included change in wind speed which effects airborne salinity, and the length of time that the surface is wet. The different results were produced by an increase in projected wind speed for Brisbane and drier weather for Melbourne. A paper by Kumar and Imam [9] suggests that the temperature rise and reduction in relative humidity projected for the UK up to 2090 would result in a 3% decrease in corrosion levels for carbon steel compared to what might be expected were they to remain at 2010 levels. Kumar and Imam also show that changes in precipitation level has a greater influence on corrosion rate than temperature and relative humidity, with a 20% increase in annual precipitation giving an 18% increase in corrosion levels. Little change in annual precipitation is projected for the UK and the impact of the increased seasonality of rainfall that is projected was not assessed. As with the Australian study the authors advise that corrosion rate changes are very site-specific as they will depend on local climate and pollution conditions.

The additional uncertainty that climate change brings, and the site specific nature of these changes makes effective risk management and monitoring of bridge deterioration even more important.

3. CURRENT MONITORING PROCESSES FOR CONCRETE ROAD BRIDGES

The key document used for the management of highway structures in the UK is "Management of Highway Structures – A Code of Practice" [10] (Bridges CoP) produced by Roads Liaison Group. This document lays out the requirements for the management of highway structures to ensure that they are safe for use and fit for purpose. All UK highway structures are subject to de-icing salts to a greater or lesser extent.

The potential detrimental effect of de-icing salts on reinforced concrete road bridges is well known and the subject of many technical papers. Inspection, testing and monitoring form the basis of good management practice. The Bridges CoP states the following:

- Provide data on the current condition, performance and environment of a structure,
- Inform analyses, assessments and processes,
- Compile, verify and maintain inventory data

This data led approach informed by the initial visual inspections helps to develop an inventory of all structures enabling them to be managed and monitored. This can lead to the development of a works programme prioritised according to agreed levels of service and available budgets.

The Bridges CoP recommends that the inspection regime should include Acceptance, Routine Surveillance, General, Principal, Special and Safety Inspections as required. The General Inspection is the main inspection used to record the condition of a highway structure at two year intervals. General Inspections comprise a visual inspection of all parts of the structure that can be inspected without the need for special access or traffic management arrangements. These documents provide an inspection pro-forma and defect classification that is used to give a Condition Performance Indicator (CPI) for the bridge.

The individual CPI values allow an individual Bridge Condition Score (BCS) to be calculated. These can be combined to give Bridge Stock Condition Index (BSCI) values for an authority's stock of highway structures.

The BSCI value can be interpreted broadly as the "percentage service potential" of a bridge stock in general. Thus a BSCI value of 100 implies that the stock has retained 100% of its service potential; a value of 60 implies that a bridge stock has lost 40% of its service potential; a value of zero implies many bridges in the stock are no longer serviceable.

To supplement this information, a Principal Inspection or more particularly a Special Inspection could be carried out on either specific structures identified as at risk within the stock or indeed particular elements of these structures. This may include materials testing for example to more clearly define exactly the elements that may require remedial works leading to inclusion in a targeted capital maintenance programme.

Generally undertaken at six year intervals, Principal Inspections comprise a close examination, within touching distance, of all accessible parts of a structure, utilising suitable access and/or traffic management works as necessary. Closed circuit television may be used for areas of difficult or dangerous access and underwater inspections are undertaken where necessary. A Principal Inspection may include a modest programme of testing when considered necessary, e.g. hammer tapping to detect loose concrete cover or half-cell and chloride measurements to enable the risk of reinforcement corrosion to be assessed.

4. PROPOSED RISK MANAGEMENT PROCESSES

4.1. Proposed risk based inspections

The requirements for the inspection of highway structures, including routine and non-routine types of inspection, are set out in BD 63/07 (Highways Agency, 2007) [11].

Recently, owners of structures assets in the UK, including rail, have begun to consider the advantages of planning a structure's inspection regime on the basis of risk. Despite the relatively sudden interest, UK highway authorities have allowed the scheduling of Principal Inspections to be based on risk assessments for many years, with BD 63/07 stating that longer Principal Inspection intervals are permitted providing a risk assessment is undertaken. Despite this, very few structures, if any, have adopted this approach to inspection. Indeed, at the time of writing, not a single one of the Highways Agency's 18,000 plus structures deviates from the standard Principal Inspection interval of six years. This is largely due to the lack of an accepted mechanism for implementing a risk based approach up to now. However, a change of approach is now starting to emerge.

The case for a risk-based approach to the inspection of structures is quite simple: *why should low-risk structures demand the same intensity of inspection as higher-risk structures?* Whilst this basic argument remains constant, the way in which different asset owners have approached the subject varies.

In December 2012, the Highways Agency published Interim Advice Note 171/12 [12]. Setting out guidance for a systematic risk-based approach to determining the Principal Inspection interval for Agency owned structures, its publication effectively encourages the Agency's Service Providers to take up the flexibility already provided by BD 63/07.The Highways Agency's methodology is based closely on one trialled by the Welsh Assembly Government. This allows engineers to score a number of criteria in order to determine risk scores for a number of categories (structure type, environment, inspection/assessment, condition and consequences) which are weighted and adjusted to give an overall recommendation for the Principal Inspection interval of an individual structure. This interval can be 6, 8, 10 or 12 years. In this respect, it is not a full risk-based approach as it does not generate intervals of less than six years for higher risk structures. The justification for this is that the Highways Agency has a number of established mechanisms in place for managing higher risk structures (e.g. Special Inspections, National Structures Programmes and BD 79/06 [13], which deals with the management of substandard structures). It is also important to note that the guidance promulgated in IAN 171/12 is a tool to help asset managers identify structures that have potential for a reduced Principal Inspection regime. It is not intended to replace engineering judgment.

Network Rail, who manage and maintain the UK's rail network, own around 40,000 bridges (compared to 9,000 owned by the Highways Agency). Network Rail bridges are generally much older, have shorter span lengths and are built from different materials to their road counterparts (where brick, masonry and steel are more commonly used than concrete). It is, therefore, unsurprising that the risk-based inspection approach adopted by Network Rail is somewhat different to the Highways Agency's approach. Network Rail have adopted a risk-based system that allows the interval between Detailed Examination (their equivalent of Principal Inspections) to be set to between one and eighteen years, with an interval of six years being the default. Visual Examinations (equivalent to General Inspections) are carried out annually during the intervening years.

Despite the differences in approach, both the Highways Agency and Network Rail share the same philosophy: that applicability of a risk-based inspection regime is not only dependent on the attributes of the structures being considered, but also on the overall structures management systems that are in place. A risk-based inspection method that works in one country, or organisation, may not be appropriate in another where inspection protocol, inspector competence or supplementary management procedures are different.

4.2. Concept for Image-based bridge inspection (a way forward?)

Visual bridge inspection is important. It is one of the main sources of information on the condition of a bridge or structure available to those responsible for the maintenance of the bridge. Most bridge inspection regimes have, at their core, a visual inspection of the condition of the bridge conducted without any special access arrangements or equipment. This inspection is typically carried out every few years, with more detailed inspections carried out less frequently. However, it is suggested that visual inspections in general, and also specifically on bridges may not provide as accurate and reliable a picture of the condition of the bridge as may be desirable.

The collection of pavement condition data used to be done largely using subjective manual inspections. In recent years however, technological solutions such as the traffic speed condition surveys available using HARRIS, TRACS, SCANNER, TSD have been embraced. These provide more objective, quantifiable, repeatable and reproducible data than was previously available using visual inspections. If similar approaches could be adopted for collecting bridge condition data then this may provide more reliable data to the end user. To date no suitable equipment has been available which would allow data to be collected at the required levels of resolution, and consequently TRL have investigated the needs of such a system in relation to such structures

TRL have developed and demonstrated the potential for undertaking image-based General Inspections, using prototype hardware. This has been tested by internal and external experts, and the results of the image-based inspections have been compared against traditional inspection data.

The development of such a system should provide a number of potential advantages over traditional data and its collection:

- The need for access to a structure should be simplified, this would be particularly helpful in areas of busy or high speed traffic, or areas of high level, difficult access
- A complete high-resolution image record of the visual appearance of the structure will be taken in a systematic manner which will enable individual defects to be tracked and trended more accurately than the current methods
- It will be easier to obtain a second opinion or discuss a particular structure or defect with other engineers as it will be possible to share the images
- It will be possible to use software to record the location, type and extent of a defect, which can then automatically produce quantifiable data regarding the condition
- Such data can be easily and directly compared from one survey to another on the same structure to monitor the change in condition
- The images will be suitable for manual or automatic interpretation, meaning that a computer based image-processing approach could be used to highlight potential areas of interest to the engineer before the final manual inspection of the images takes place

Additionally, TRL are investigating ways of combining high resolution images with 3-D shape data of the bridge in order to produce interactive 3-D models of the bridge. These can be very useful and informative in terms of visualising the effect of particular defects and the condition of a bridge and replacing some of the context lost when looking at a series of individual 2-D images.

5. INNOVATIVE METHODS OF MANAGING RISK OPERATIONALLY

5.1. The need to reduce chloride use

Recent innovations in guidance on spread rates for de-icers, better forecasting, different de-icer types and better spreading technologies have greatly reduced the amount of de-icer required to achieve the required service levels for the winter service of roads. However, where a road bridge is part of a route that is required to be kept free of ice and snow to ensure free movement of traffic during winter conditions two distinct and opposing sets of problems are presented for the road/bridge owner and operator. On the one hand is the necessity to keep the road and bridges on a route clear of ice and snow, on the other there is the potential damage to the bridge and its components caused by the de-icing chemicals.

At the same time it is well understood that sodium chloride salt is often responsible for a significant amount of damage to bridges and similar structures through corrosion. There are other de-icer salts that can be (and are) used with less corrosive properties. There are also "alternative de-icers" that do not contain chlorides such as acetates, formates and urea which are used to prevent damage to structures and reduce corrosion. These de-icers are less widely used being more expensive to purchase and more costly to deliver. Their impact on the environment must also be considered. There are also some significant practical difficulties associated with attempting to treat bridge decks separately from the road itself.

In summary, it can be seen that the most common and generally accepted as the most economical way of treating roads and bridges with salt, widely employed by the majority of owner/operators, is also one of the more damaging options in terms of corrosion of structures. At the same time bridges in themselves also present some unique problems in requirements for winter service. These problems are for a number of reasons:

- Lower thermal capacity of the deck structure
- Greater surface exposure to cooling (e.g. through the soffit as well as the surface of a bridge deck)
- Greater exposure to cooling winds and precipitation
- More condensation on the surface before freezing temperatures are reached.

These are among a number of influences which mean that a bridge will often require treatment earlier and with more de-icer than the adjoining road. In order to understand better the practical issues caused by this it is first necessary to have a broad understanding of efficient delivery of winter service to roads and current best practice.

5.2. Innovation and the Optimised delivery of de-icing agents

Driven by the need for lower costs, increased resilience of the winter service by preserving salt stocks, reducing damage to the environment and generally delivering a more efficient service has resulted in considerable recent innovation in the winter service area. Recently, the results of many years of research and trials carried out by TRL on behalf of Highways Agency, Transport Scotland and the National Winter Service Research Group (NWSRG) has been applied to the production of new UK guidance on winter service. This shows that far lower salt rates may be used than previously given and used (in the UK) where the right materials, equipment and conditions are available. These rates are particularly lower (than those previously used) when spreading at marginal temperatures, i.e. near to and just below freezing.

The de-icers considered have included magnesium and calcium chlorides either on their own or mixed with sodium chloride and also with ABP (Agricultural By-product) additives. These have not only been shown to be more effective at lower temperatures but also reduce the amount of sodium chloride required either by replacing it or making it more effective so that less is needed.

The work on alternative de-icers has been focussed on extreme cold conditions (defined as below -5 ^{o}C to -7 ^{o}C (depending on humidity) for the UK and limited by the effective lowest temperature for the spreading of salt and -15^{o}C as the lowest temperature at which salt can be considered to work for practical purposes). While salt theoretically prevents freezing down to -22°C, when used as a road de-icer the rate of dissolution at low temperatures and the effect of dissolved ice lowering the concentration of the brine results in the -15°C limitation. It has been considered that further work looking at the effectiveness of the alternative de-icer combinations indicated above may show benefits in reduction of sodium chloride and a more economical, less structurally and environmentally damaging winter service for temperatures between -7°C to 0°C. All of this appears to be potentially beneficial for bridges and structures in reducing exposure to chlorides and particularly sodium chloride, however there are several factors to consider.

Minimum spread rates for de-icers are achieved by spreading at the optimum time for the conditions which principally involve forecast temperature, road surface wetness and traffic. Generally the lower the forecast temperature and the higher the roadsurface wetness then the more de-icer is required. While some traffic helps crush salt grains so they dissolve more quickly, heavier traffic may disperse salt either as particles or brine spray, off of the road and, where near or on a bridge, onto surrounding structural components. Traffic also helps to disperse water from the road surface, so delaying spreading on a wet road until the water is dispersed reduces the salt required.

In summary the optimal timing of the treatment for a road may depend on traffic (all other conditions being equal) and should often be delayed for as long as possible to avoid loss of de-icer and to disperse surface water if present. This will help to limit the dispersal of salt / spray onto other bridge elements and indeed reduce the need for further reapplication – both these outcomes would be helpful to reducing the effects of chloride on reinforced concrete.

5.2.1. Advanced spreading technologies

The use of advanced or different spreading technologies may help reduce the amount of salt but does not offer a complete answer. Spreading technologies using a mix of dry salt and a fully saturated brine solution (pre-wet spreading) provide advantages in spreading accuracy as some brine is provided which will have an immediate de-icing effect, however the remaining salt spread with the brine still requires further water to go into solution. Another spreading technology using just pure brine is also an option however due to the large quantities needed, particularly at lower temperatures, may be impractical due to the amount of liquid that can be carried by the delivery vehicle (brine spreader) restricting the length of road that can be covered in one run. The use of brine spreaders, particularly if they use a non sodium chloride brine could be beneficial if the spreading was carried out both at the bridge and to 1 km either side (for twin dual carriageways and above it would only need to be 1km on the approaching carriageway, however the effect of the traffic on transportation of salt away from the road immediately after the bridge would need to be considered to ensure it was being replaced at an adequate level by the de-icer used on the bridge. This is also a more costly solution than using a single spreader for an entire route.

The type of road surfacing used should also be considered. Some negatively textured surface courses will hold water or brine due to their porous nature. This can be beneficial if they hold brine but detrimental if they hold water (e.g. after rain) as more salt will be required. Dense surfacings such as hot rolled asphalt (HRA) do not present this problem. There are also proprietary surfacings of various types which claim to overcome problems with ice formation however these would need to be tested over a range of conditions in order to ascertain their suitability and limitations.

Another method of protecting against ice formation and to ensure snow does not bond to the road surface is to provide a standalone (installed) system on the structure itself spreading a non-corrosive de-icer or using some form of heating of the surface.. Where a heated system is used de-icer would still be transported onto the bridge and the effect of salt being transported down the road after the (particularly a long) bridge could leave that section of road with less de-icer than required.

It can be seen that the issues outlined here point to the consideration of winter service provision at the bridge design stage. Factors which would reduce some of the problems include:

- Ensuring components are resistant to sodium chloride corrosion or protected from sodium chloride reaching them
- Adequate drainage routing brine away from sensitive components should be installed and consideration should be given to managing brine seepage if the waterproofing system and expansion joint fail.
- The surfacing material for the bridge deck can also play an important role in winter service requirements.

6. REDUCING RATES OF CORROSION IN REINFORCED CONCRETE BRIDGES

One of the most reliable ways of continuously and systematically controlling corrosion of the steel reinforcement is by electrochemical means. All electrochemical remediation techniques applied to steel reinforcement in concrete are similar in nature. They all polarize the steel in a negative (cathodic) direction ensuring that the steel behaves primarily or totally as a cathode and as such does not corrode, or corrodes at an acceptably low rate. What differs in the techniques is the nature and properties of the anode which can either be sacrificial (i.e. is consumed in preference to the steel) or essentially inert driven by an external power source. The level of polarization and whether it is permanent or temporary, plus the use of additional current carrying electrolyte and the electrochemical reactions induced at the anode and cathode, define the technique and what it is aimed at achieving.

Cathodic protection (CP), the more commonly used electrochemical technique to mitigate or stop corrosion of steel in concrete, functions by applying a small direct electric current from an external source in order to suppress the 'internally generated' current flow due to the corrosion processes. The 'external' current source can be obtained by coupling the steel to another electrochemically more active metal such as zinc (Sacrificial or Galvanic Anode Cathodic Protection, SACP) or, more commonly the 'external' current may be provided by a low voltage direct current (DC) power source (Impressed Current Cathodic Protection, ICCP).

CP of reinforced concrete highway structures has been rigorously assessed, both in the UK and internationally, and demonstrated to be reliable and effective in controlling corrosion of reinforcing steel in chloride-contaminated concrete. Experience on such structures has demonstrated that the use of CP, as an alternative to extensive removal and repair of chloride-contaminated but sound concrete with its consequential noise, dust and disruption, can significantly reduce contract costs, particularly when contract durations are reduced and the need for structural propping is avoided. The reduction of large scale concrete removal and reinstatement can result in contract cost reductions of between 20% and 80% when compared with extensive repair methods. As a result, CP has been adopted as the major rehabilitation method to stop corrosion on the Midland Links structures (figure 2), with more than 100,000m^2 of concrete being protected using the technique. The high confidence gained in CP in this environment has lead to its wide application elsewhere in the UK.

Figure 2 - Conductive Paint Anode Cathodic Protection System on typical Midland Links substructure.

CP is considered to be a sustainable option as it is making the most of the structure in its current form and extending its life through relatively minor repair work. It also results in less waste going to landfill as often relatively little concrete is broken out and repaired.

Satisfactory CP system performance before maintenance can be expected to range from 10 to 40 years, depending upon system type, with embedded components of some systems having a theoretical design life of up to 120 years. However, electrical power supply and monitoring systems are likely to require replacement every 20 to 40 years.

The decision on which systems to use is usually influenced by a number of factors including but not limited to the condition of the structure, the client's budget and the anticipated life expectancy of the structure following the repairs.

6.1. Impressed Current Cathodic Protection (ICCP)

The majority of CP systems applied to reinforced concrete structures internationally, and particularly in the UK, are impressed current cathodic protection (ICCP) systems. ICCP systems arrest steel reinforcement corrosion activity by supplying electrical current from an external source to overcome the on-going corrosion current in the structure.

ICCP involves the permanent installation of a low voltage, controlled electrical system which passes direct current to the steel. The anode can be applied on the surface of or drilled into small holes in the structure. ICCP provides protection that can be effectively monitored and controlled in the long term.

The main components of a typical ICCP system include the anode system, reinforcing steel, electrolyte (in the concrete), cabling, monitoring devices e.g. reference electrodes and a DC power supply. The current output of the power supply can be adjusted to optimise the protection delivered. ICCP systems can be controlled to accommodate variations in exposure conditions and future chloride contamination.

The durability of ICCP systems is largely determined by the choice of anode. This is because the damaging reactions are moved from the steel to the installed anode. There are a number of impressed current anode systems for reinforced concrete on the market. These include conductive coatings, titanium based mesh in cementitious overlay, conductive overlay incorporating carbon fibres, flame-sprayed zinc and various discrete anode systems (Figure 3). There are a range factors which influence the selection of impressed current anodes for ICCP systems. These include environmental conditions, anode zoning, accessibility, maintenance requirements, performance requirements and operating characteristics, life expectancy, weight restrictions, track record and costs.

Figure 3 - MMO Coated Titanium Mesh Anode in Cementitious Overlay on Cromarty Viaduct Pier on the A9 in the north east of Scotland

6.2 Sacrificial Anode Cathodic Protection (SACP)

A sacrificial anode cathodic protection (SACP) system uses an anode made from a metal or alloy from the galvanic series which has a more negative electrochemical potential than the steel reinforcement of the structure. This works because the difference in potential between the anode and steel causes a positive current to flow in the electrolyte, making the steel more negatively charged, thus becoming the cathode. The difference in potential between the steel reinforcement and the sacrificial anode, indicated by their relative positions in the galvanic series, means that the galvanic anode corrodes (sacrificed) in preference to the steel. The sacrificial anodes are directly electrically connected to the steel to be protected. The metals commonly used as sacrificial anodes are aluminum, zinc and magnesium. These metals are also alloyed to improve the long-term performance and dissolution characteristics.

6.3 Impressed Current Cathodic Protection CP (ICCP) versus Sacrificial Anode Cathodic Protection (SACP) to manage corrosion risk

Impressed Current CP (ICCP)	Sacrificial Anode Cathodic Protection (SACP)
• Controls corrosion at any chloride level	• Chloride levels affect the rate of anode consumption
• 30 year design life, longer life is possible	• Anode lifespan uncertain
• Electrical components & cabling last about 20 years	• Cannot tell when the anodes are used up
• Electrical power required.	• External power is not required
• System requires regular monitoring and maintenance	• Surveys required to monitor systems which can be part of the inspection regime
• Components and control equipment are vulnerable to environmental conditions including vandalism	• Systems are not vulnerable to external conditions
• Risk of hydrogen embrittlement on high strength steels	• Little risk from hydrogen embrittlement
• Stray currents must be controlled near rail infrastructure	• Low risk of cathodic interference in adjacent structures

7. CONCLUSIONS

Currently within the UK there are a number of factors that are indicating a need to review current concrete bridge inspection, monitoring and protection regimes to ensure long term life and cost effectiveness of the asset.

With the changing climate conditions predicted within the UK there seems to be a significant likelihood of corrosion rates increasing - corrosion due to chlorides is already the most serious cause of deterioration within the concrete bridge stock in the UK, with the concrete bridge stock comprising an aging and very significant proportion of the infrastructure.

This paper has considered the role of bridge inspection, monitoring, and corrosion protection measures in managing the risk of corrosion. This has included how the necessary de-icing agents, in particular sodium chloride (common salt) could be applied utilising more effective and efficient methods, certainly for ranges of temperatures between -7^{o}C to 0^{o}C, and in doing so limit concrete bridges' exposure to chlorides.

It has also been highlighted in this paper that there a need to consider winter service provision at bridge design stage and design and detail accordingly.

Long established techniques such as CP remain available and valuable in combating corrosion where it may be predicted or already present as a cost effective alternative to intrusive repairs. In general terms SACP is considered more suitable for smaller and targeted repairs, where current output demands are lower and where budgets and or life expectancy are limited. ICCP is generally used to address significant corrosion problems to large structures and surface areas, where a longer life expectancy is required and where access and traffic management are challenging and costly. The choice of technique and anode used will depend on a number of factors including condition of the structure, environmental conditions, accessibility and maintenance requirements. The bridge stock owner's available budget, likely to reduce due to current austerity measures is a key factor in the UK.

The case for a risk-based approach to the inspection of structures is quite simple and has been demonstrated: why should low-risk structures demand the same intensity of inspection as higher-risk structures? Whilst this basic argument remains constant, the way in which different asset owners have approached the subject varies.

Interim Advice Notes setting out guidance for a systematic risk-based approach to determining the Principal Inspection intervals for example have been published recently to encourage the uptake of risk management of such structures which has been an option in the UK for a number of years. Implementation of such an approach should not be considered a replacement for engineering judgement and it is recognised that what works in one country, or organisation, may not be appropriate in another where inspection protocol, inspector competence or supplementary management procedures are different.

In order to better manage risk further and reduce the level of human intervention and therefore cost, new high resolution images and 3D models are becoming available allowing more detailed and reliable inspections to take place, but reducing the need to continually access the structure directly and improve the sharing of condition data for example.

However it is the risk averse nature of engineers and bridge managers that has hindered the uptake of this approach so far. Climate change, combined with decreasing budgets and resources may drive its uptake in the future.

It is clear from the findings in this paper that techniques and systems are now available to facilitate the implementation of effective risk management leading to a more targeted, predictive and cost effective approach to maintaining the concrete bridge infrastructure in the UK.

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