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INTEGRATED MONITORING SYSTEM FOR DURABILITY ASSESSMENT OF CONCRETE BRIDGES

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An ageing and deteriorating bridge stock presents the bridge owners with the growing challenge of maintaining the structures at a satisfactory level of safety, performance and aesthetic appearance within the allocated budgets. This task calls for optimized bridge management based on efficient methods of selecting technical and economical optimal maintenance and rehabilitation strategies. One of the crucial points is the assessment of the current condition and future development and performance.

Selecting the optimal maintenance and rehabilitation strategy within the actual budget is a key point in bridge management for which an accurate assessment of performance and deterioration rate is necessary. For this assessment, the use of an integrated monitoring system has several advantages compared to the traditional approach of scattered visual inspections combined with occasional on-site testing with portable equipment and laboratory testing of collected samples. For this reasons, attention is more and more focusing on the development of permanent integrated monitoring system for durability assessment of concrete bridges.

It is estimated that with the implementation of such integrated monitoring systems, it should be possible to reduce the operating costs of inspections and maintenance by 25% and the operator of the structures will be able to take protective actions before damaging processes start.

This paper identifies the main bridge owner requirements to integrated monitoring systems and outlines how monitoring systems may be used for performance and deterioration rate assessment to establish a better basis for selecting the optimal maintenance and rehabilitation strategy.

1. Introduction

The major part of the European infrastructure has reached an age where capital costs have decreased. However, inspection and maintenance costs have grown such extensively, that they constitute the major part of the current costs. An ageing and deteriorating bridge stock presents the bridge owners with the growing challenge of maintaining the structures at a satisfactory level of safety, performance and aesthetic appearance within the allocated budgets. This task calls for optimized bridge management based on efficient methods of selecting technical and economical optimal maintenance and rehabilitation strategies. One of the crucial points is the assessment of the current condition and future development of deterioration and performance.

Numerous management and rehabilitation strategy have been developed to assist engineers in deciding what maintenance is required and when it should be carried out. The simplest consists of a database that holds all the relevant information on each structure – for example structural details, records of inspections, previous maintenance history – that the engineer needs to reach a decision. Systems that are more complex contain algorithms that manipulate the data to produce optimum maintenance strategies, taking into account constraints such as inadequate funding.

Selecting the optimal maintenance and rehabilitation strategy within the actual budget is a key point in bridge management for which an accurate assessment of performance and deterioration rate is necessary. For this assessment, the use of a integrated monitoring system has several advantages compared to the traditional approach of scattered visual inspections combined with occasional on-site testing with portable equipment and laboratory testing of collected samples. For this reasons, attention is more and more focusing on the development of permanent integrated monitoring system for durability assessment of concrete bridges.

The SMART STRUCTURES-project BRPR-CT98-0751 has been funded by the European Commission in the period 1998-2002. Within this project, eight European partners have developed an integrated monitoring system with new sensors, data acquisition and transfer facilities as well as interpretative software, which cover the need for durability monitoring of existing concrete structures [1].

The important part of this project was concerned with development of different sensors to be embedded in concrete structures as a part of the monitoring system. These sensors should register time to corrosion initiation, chloride content and humidity. Laboratory tests have been performed with the new developed sensors measuring the above-mentioned parameters. Based on the laboratory tests calibration curves for translation of monitored data on-site tests have been established. The on-site test is being conducted on the highway bridge near Copenhagen with sensors installed during 2000 and 2001 in approx. 200 positions. The monitoring on-site will continue for the next five years and it should contribute to the further improvement of the sensors [1], [2].

This paper identifies the main bridge owner requirements to integrated monitoring systems and outlines how monitoring systems may be used for performance and deterioration rate assessment to establish a better basis for selecting the optimal maintenance and rehabilitation strategy.

2. Traditional Bridge Management

Traditional bridge management includes three basic types inspection:

a) Routine inspections, typically simple, superficial visual inspections, which result in only minor cleaning and maintenance activities.

b) General or principal inspections, typically more extensive visual inspection, resulting in some maintenance activities at long term intervals.

c) Special inspections are carried out on structures where there is a particular problem or cause for concern. This may result in larger rehabilitation activities, test loadings, realistic safety assessments, etc.

The routine inspections are carried out often (*e.g.* once a year), whereas the general inspections are carried out with larger intervals (*e.g.* every five years). The inspection intervals are often fixed in regulations, guidelines or even in national laws or based on the latest principal inspection.

Based on the special inspection, the engineer will usually consider a number of alternatives maintenance and rehabilitation strategies [1], [3]:

a) Postpone any action for another 5 or 10 years (or until next special inspection).

b) Minor cleaning and repairs.

c) Extensive rehabilitation of parts of the structure (often several choices).

d) Replacement of the structure.

The special inspections usually lead to an assessment of the structures performance (safety and functionality) and a prediction of the development over another 5, 10 and 20...25 years in order to estimate the economical and technical consequences of taking or postponing the actions.

3. Advantages and Disadvantages of Traditional Bridge Management

In general, most countries rely on scattered visual inspections with occasional on-site testing with portable equipment and laboratory testing of collected samples, to assess the state of the bridges. The interval between the inspections and the required level of detail differ from country to country. Visual inspections are relatively simple, "low-technology" procedures, whose easiness of execution and repetitively have contributed to their success. Therefore, they form long historical records and constitute the fundamental know-how on the evaluation of deterioration of bridges (Table 1).

Table 1
Advantages and Disadvantages of Traditional Bridge Management

Problem	Present Situation	Result	Advantages	Disadvantages
Evaluation of the actual state of bridges	visual inspections	gross estimate of the condition of bridges	– repetitive – low cost	– far from the structure – disturbance to traffic – subjective evaluation
Evaluation of the future state of bridges	– *in situ* testing (concrete and reinforcement) – laboratory testing on cores; – numerical models to describe deterioration	more exact estimate of the condition of bridges	– non-destructive – (repetitive over time) precise evaluation – (few points over time) – information on the structural behaviour	– when needed – disturbance to traffic – disturbance to structure (cores) – few measures, few points on curves
Maintenance planning	– maintenance options – unit cost of repair – numerical procedures	– choice of correct type and time to repair – allocation of money	total cost of interventions	reliability of computations affected by uncertainties inherent in the previous steps

This traditional bridge management has some apparent drawbacks such as [4], [5]:

a) Traffic interference during inspection and testing.

b) High costs of providing access to the structural elements.

c) Scattered data makes prediction of the time for initiation of deterioration and the future damage growth less accurate.

d) Infrequent inspection and testing may allow deterioration to progress between inspections to an extent that makes efficient and cheap preventive maintenance and rehabilitation strategies impossible.

On the other hand, one of the main shortcomings is that damage is only visual and even if its extension may be evaluated, no structural information may be directly inferred. Furthermore, as inspections are often conducted from the ground, far from the structure, some types of damages may escape the inspection. For instance, cracks, which can be a sign of corrosion of reinforcement in concrete structures, may not all be detected.

Another problem is given by the subjective nature of the ratings that are attributed by the inspectors based on their experience. A large scatter in damage ratings may be found among different engineers.

Ratings are not an exhaustive evaluation of the conditions of the bridges. To gain a deeper insight on the safety of the structures, recourse has to be made to testing. Even if tests give a reliable evaluation of the structural relevance of damage, they are not systematically conducted. Not all tests are simultaneously performed. This means that we may have only data on concrete for a given structure or dynamic testing, etc., and they are often not located where visual damage has been spotted. This implies a difficulty in inferring curves of structural deterioration in both time and space along the structure.

Most of the testing results in unbiased values that can support the often very subjective results from the visual inspections. Repeated testing provides crucial reference data for the damage development models.

However, it is desirable to do as little coring and other destructive testing as possible, since it can have consequences for the aesthetics and durability around the testing positions. Furthermore, it must be secured that the bearing capacity, *i.e.* safety is not put at stake.

Testing will always give a result valid for the exact time of testing only. For deterioration mechanisms, where the measurable parameters vary with climate and season, a true picture of the deterioration will not necessarily be found [6].

The process of decision making and planning of maintenance and repairs suffers from all the uncertainties inherent in both the practice of visual inspections and in the testing procedures. In particular, uncertainties and errors grow larger and larger as projections of the future states of structures are extended over time. It is therefore desirable to find alternative ways to assess the conditions of bridges.

4. Integrated Monitoring System

The main objective is to develop an integrated monitoring system for durability assessment of existing and new concrete bridges. The system must interface and integrate the actual practice mainly based on visual inspections and combines the response of a number of different reliable sensors, installed on the structure to monitor the progress of damage, with enhanced realistic deterioration models. The system and the sensors were developed to cover the parameters for the most important deterioration mechanisms: corrosion of reinforcement in bridges, carbonation of concrete, freeze – thaw cycles, alkali – silica reaction and mechanical damage, as well as the changes in the structures behavior and safety: static deformation, strains, crack widths and vibrations (frequencies, amplitudes, accelerations and vibration modes) [1].

The progress of the various types of damage mechanisms can be predicted by monitoring the key physical and chemical parameters of the materials (such as temperature, humidity and pH for the concrete, measured on the surface of the structure and as a profile through the concrete thickness, (and rate of corrosion of reinforcement), and key mechanical parameters (such as strains, deflections, vibrations). As the sensors have to be permanently installed on the structure, they must present special characteristics of durability, easiness of installation and substitution, apart from being obviously low cost.

The next point concerns the acquisition of the data collected on site and their transmission to a remote PC. All data must fit into numerical models to represent and to predict the deterioration of concrete bridges. Finally, the last component of the integrated monitoring system is given by software able to help in assessing the strategies of intervention for the individual bridges.

These strategies must be defined by associating to the prediction of structural deterioration the corresponding evaluation of costs of intervention, computed as functions of the different levels and types of deterioration, and the corresponding costs of traffic interference.

5. End User Requirements for Integrated Monitoring

The bridge owners' main interest in permanent monitoring systems for durability and performance assessment of concrete bridges is to reduce the inspection, maintenance and rehabilitation costs as well as the traffic interference and yet still maintain a satisfactory level of safety, performance and aesthetic appearance [7].

A permanent monitoring system should assist the bridge owner in selecting the optimal maintenance and rehabilitation strategy by providing (Table 2):

a) Input to the maintenance and rehabilitation strategies in order to select the optimal preventive and remedial actions.

b) Timely warnings of initiation of durability and structural problems making preventive actions possible.

c) Timely warnings to ensure the safety of the structure, in particular for structures that can collapse without any *prior* sign of deterioration.

d) Input to future inspections of the structure including the time, extent and frequency of inspection, structural elements and deterioration mechanisms to focus on and additional on-site or laboratory testing (if any).

e) Improved knowledge of the performance to validate the design assumptions.

f) Improved knowledge of the individual deterioration mechanisms and their interaction.

Table 2
Requirements for Permanent Monitoring Systems

Process to monitor	Relevant parameters	Location	Component of the system	Requirements
– corrosion – freeze–thaw – alkali–silica reaction - mechanical damage	– humidity/moisture content – temperature – pH – chloride content – corrosion initiation/rate – permanent deflections – cracks – static and dynamic behavior (structural safety)	areas critical: – safety – development of deterioration	sensors/probes	– robust – accurate – durable – easy to install/operate – low cost
			empirical models	reliable trends of deterioration
			data acquisition	– automatic acquisition – adjustable frequency –manual measurements still possible
			data transfer	– remote communication site/office
			software for data treatment	– early warnings – compatible with standard programs

The knowledge on the development of deterioration of structures, in both its aspects of initiation and quantification, represent a key activity for the management of bridges, especially where it deals with the planning of maintenance and repair activities. It is particularly difficult to assess the conditions of bridges and to foresee the evolution of their damage as this process is affected by many factors, some of which interact and some of which have no measurable effects. Permanent monitoring systems should therefore provide information that can be used as input for the decision making process (*e.g.* for estimating the extent and budgets for maintenance, rehabilitation and repair activities) such as probable deterioration mechanisms, estimates of the time for initiation and future development of deterioration, assessment of structural safety.

Permanent monitoring systems should be able to monitor the relevant deterioration mechanisms such as corrosion of reinforcement initiated by chloride ingress or carbonation, freeze–thaw damage and alkali–silica reaction damage. Ideally, one or more measurable key parameters that can describe the progress towards initiation and subsequent growth of damage should be identified for each deterioration mechanism as well as simple deterioration models allowing for prediction of the initiation and growth of damage. Furthermore, the structural performance and the effects of *e.g.* mechanical damage due to deterioration, vehicle impact, overloading or loss of prestressing should be covered by the monitoring system.

To be effective, a permanent monitoring system must include a number of sensors installed on the structure, a data acquisition/transfer system and integrated software for analysis and treatment of information. A number of requirements are therefore mandatory for the owner. First, sensors and probes have to monitor relevant key parameters accurately. They must have a long service life, be easy to install and to operate (traffic interference) and have a limited need for maintenance and calibration. The data acquisition system should allow for adjustable measuring frequency (preferably on-line control), two-way communication between site and office, and send out warnings if parts of the system have stopped working [8].

The software should be compatible with recognized standard programs. Results and data for daily operation or for research purposes should be easily accessible. The software should enable a precise identification and detailed overview of the location of monitoring devices (preferably shown on a drawing of the structure). It should be possible to get an evaluation of the areas that the individual sensors represent to give a reliable picture of the condition of the entire structure. The software should enable a simple and easy to understand presentation of the development of the monitored key parameters, *i.e.* the history, current situation and future development based on simple models for extrapolation to result in quick answers for the end users in the light of the management of bridges.

Models for deterioration, based on measurable parameters, should be integrated into the software to predict the initiation of deterioration and the future deterioration rate. Models for service life predictions should be based on recognized physical principles. Timely warnings of critical damage levels in relation to both durability and structural safety should be given.

6. The Main Tasks of the Research

The process to develop an integrated monitoring system for durability assessment of existing and new concrete bridges is divided in seven tasks (Fig. 1) [1], [2]:

Task 1 describes the state of the art of current practice in the fields of inspections, monitoring and maintenance, both in European Community and in the USA, underlying advantages and possible disadvantages as well. These inspections are also carried out for a variety of other reasons, for example on bridge foundations after flooding, and on structures after earthquakes. They involve extensive measurements on site and may include laboratory testing.

The results of an inspection are used to provide as a measure of the structure's condition. Two approaches have been used: the first is based on a cumulative condition rating obtained from a weighted sum of all the assessments of the condition of each element. The second gives the assessed condition of the bridge as the highest condition rating of the bridge elements.

Artificial intelligence methods must investigated as a means of improving condition assessment and a review was undertaken of neural network, fuzzy logic and genetic algorithms. A neural network model can be developing for categorizing the condition of corroded areas on reinforced concrete bridges.

Task 2 concerns the description and correlation of the most relevant deterioration mechanisms for the structures with the parameters that may be measured on site. The focal point is the determination of the critical levels of both the parameters of the models and of the corresponding measurable parameters.

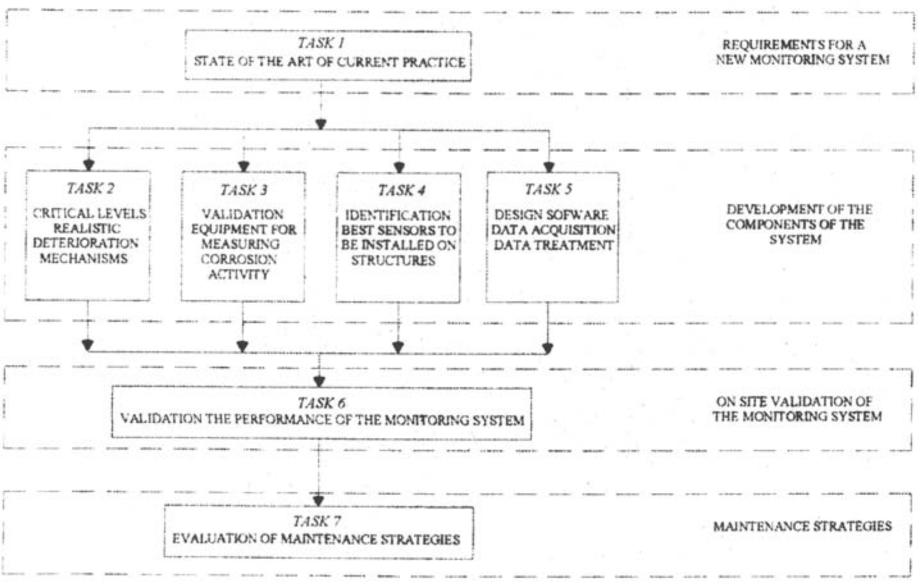

Fig. 1.– Integrated monitoring system.

Task 3 is related to the implementation of portable equipment to measure corrosion activity. This equipment may be used to support the current activity of monitoring and inspection of bridges.

The objective of *Task 4* is to identify the most indicated sensors to be installed on the bridges to monitor their progressive deterioration. They have been firstly tested in laboratory and next installed and tested on a new or existing bridge.

Task 5 aims at designing and integrating the systems for data acquisition and transfer with the software for data treatment and analysis.

Task 6 represents the validation of the whole system that has been installed on an existing or new bridge in Romania. Data collected on site and transferred according to the results of Task 5, are processed to evaluate the progress of deterioration, to define alarm thresholds and to establish maintenance strategies and compute the overall costs.

Finally, *Task 7* deals with the technical validation of the entire integrated system.

7. Expected Advantages

The integrated monitoring system should be able to help the end-user in his daily and long term management of the bridges. The use of permanent monitoring systems has several advantages once the system is installed:

a) Traffic interference is reduced.

b) The costs of access to the structure and resources for inspection and testing are reduced too.

c) Structural elements with difficult access are easily monitored.

d) A more precise evaluation of the actual conditions of the structures with particular regard to the timely warning of the onset of durability and structural problems.

e) A more reliable prediction of the progress of damage as a function both of the measured parameters and of the application of realistic deterioration models, as well as a better understanding of individual deterioration mechanisms and their interaction.

f) An input for undertaking preventive actions for low levels of deterioration.

g) An input for defining maintenance and repair strategies (time and extent) as a function of the actual and foreseeable levels of deterioration.

h) A feedback on the effectiveness of repairs.

i) An evaluation of the need for further inspection and testing.

It is estimated that with the implementation of such integrated monitoring systems it should be possible:

a) to reduce the operating costs of inspections and maintenance by 25%;

b) to reduce the traffic-related costs by 30% by reducing the number and extent of site inspections;

c) to reduce the overall life costs of bridges by 10% by applying the improved lifetime prediction models already from the design stage;

d) the operator of the structures will be able to take protective actions before damaging processes start.

8. Durability and Performance Assessment

Assessing the durability and performance of concrete bridges as a part of selecting maintenance and rehabilitation strategies involves several complicated decisions. A permanent monitoring system should assist the bridge owner in handling these questions and decisions to ensure optimal planning of the future management of the bridge including inspection, maintenance and rehabilitation. The use of a permanent monitoring system for durability and performance assessment can be described based on Fig. 2.

The first step (*1*) is to determine whether deterioration has started or not. Usually this question is answered based on visual inspection, on-site or laboratory testing (traditional bridge management), and the results from the integrated monitoring system. However, with an identification of critical levels for initiation of deterioration of the key parameters measured with the monitoring system, the results from the monitoring system can be used to determine whether deterioration has started or not.

If deterioration has not started, the bridge owner is interested in identifying the possible risk and cause of future deterioration (*2*) and in estimating when deterioration will be initiated (*3*) in order to make timely and cost efficient decisions regarding preventive actions (*4*). This requires an identification of the level for initiation of deterioration of the measured key parameters (s. Fig. 3 *a*) as well as models for predic-

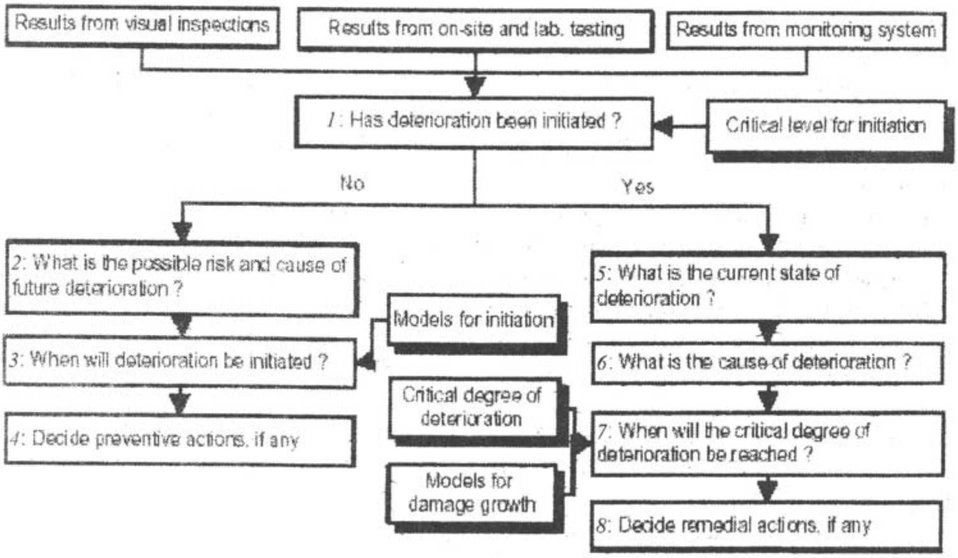

Fig. 2.– Durability and performance assessment.

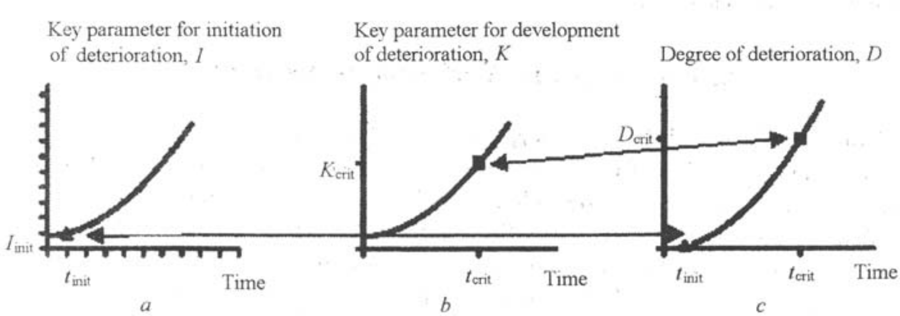

Fig. 3.– Key material parameters.

ting the future development of the key parameters for initiation of deterioration. If deterioration has started, the bridge owner is interested the current state of deterioration (*5*) and the cause of deterioration (*6*). It must be determined whether the results from the monitoring system alone are sufficient to answer these questions or whether monitoring has to be supplemented by visual inspection, on-site or laboratory testing.

The next step (*7*) is to estimate when the critical degree of deterioration has been reached in order to determine cost efficient remedial actions (*8*). This requires an identification of the critical degree of deterioration (s. also Fig. 3 *c*), *i.e.* the degree of deterioration above which the condition of the structure is unacceptable for safety, performance or aesthetic reasons. Additionally, the critical level of the measured key parameters for development of deterioration (damage growth) corresponding to the critical degree of deterioration, must be defined (s. also Fig. 3 *b*) as well as models for predicting the future development of the key parameters for damage growth. When the future damage growth has been estimated, it can be determined when the critical degree of deterioration will be reached.

The main objective is to develop a methodology for selecting an optimum maintenance strategy for a given bridge, considering safety, durability, functionality and socio-economic issues. A method must be developed which will be base of a global cost analysis which took account of all the costs involved in construction, inspection, maintenance, repair, failure, road usage and replacement. This method must minimize the global cost while keeping the lifetime reliability of bridge above a minimum allowable value.

Results from steps *1,...,8* were brought together to produce a framework for a bridge management system. For example, the assessment of bridge strength is required for the evaluation of the routing of abnormal vehicles and for the management of safety measures. The philosophy adopted in the development of the framework has been to identify the outputs required by the engineer and then determine the inputs required to produce those outputs.

9. Conclusions

An ageing and deteriorating bridge stock presents the bridge owners with the growing challenge of maintaining the structures at a satisfactory level of safety, performance and aesthetic appearance within the allocated budgets. This task calls for optimized bridge management based on efficient methods of selecting technical and economical optimal maintenance and rehabilitation strategies. One of the crucial points is the assessment of the current condition and future development of deterioration and performance.

The integrated system for monitoring and assessment of concrete bridges will result in an improved knowledge of individual mechanisms and their interaction, and in early warnings of initiation and progress of durability and structural problems, thus finally reducing inspection, maintenance and rehabilitation costs as well as traffic delays.

This system may easily integrate and supplement the current practice in the field of inspection and testing and assist the end-user in the planning of maintenance programs. Additionally the operator of the structures will be able to take protective actions before damaging processes start. Their application will result in reduced costs of inspection and reduced interference to traffic.

The use of permanent monitoring systems has several advantages once the system is installed:

a) Traffic interference is reduced.

b) The costs of access to the structure and resources for inspection and testing are reduced.

c) Structural elements with difficult access are easily monitored.

d) A more precise evaluation of the actual conditions of the structures with particular regard to the timely warning of the onset of durability and structural problems.

e) A more reliable prediction of the progress of damage as a function both of the measured parameters and of the application of realistic deterioration models, as well as a better understanding of individual deterioration mechanisms and their interaction.

f) An input for undertaking preventive actions for low levels of deterioration.

g) An input for defining maintenance and repair strategies (time and extent) as a function of the actual and foreseeable levels of deterioration.

h) A feedback on the effectiveness of repairs.

i) An evaluation of the need for further inspection and testing.

j) Frequent collection of data enables more reliable trends for the development of deterioration and performance, *e.g.* the progress towards initiation of deterioration and future damage growth.

It is estimated that with the implementation of such integrated monitoring systems it should be possible:

a) to reduce the operating costs of inspections and maintenance by 25%;

b) to reduce the traffic-related costs by 30% by reducing the number and extent of site inspections;

c) to reduce the overall life costs of bridges by 10% by applying the improved lifetime prediction models already from the design stage;

d) the operator of the structures will be able to take protective actions before damaging processes start.

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SISTEM INTEGRAT DE MONITORIZARE PENTRU SPORIREA DURABILITĂŢII PODURILOR DIN BETON

(Rezumat)

Îmbătrânirea şi, implicit, deteriorarea stocului de poduri aflat în administrare la nivel naţional, impune efectuarea în condiţii optime a lucrărilor de întreţinere care să asigure exploatarea podurilor în depline condiţii de siguranţă şi confort. Acest obiectiv necesită aplicarea unui management al podurilor bazat pe metode eficiente de selecţie a strategiilor tehnice şi economice optime de întreţinere şi reabilitare. Un parametru esenţial în aceste strategii constă în asigurarea condiţiilor necesare aprecierii corecte a stării tehnice a podurilor şi predicţia apariţiei proceselor de degradare.

Este prezentat un sistem integrat de monitorizare a structurilor de poduri din beton, care se propune a fi utilizat în scopul aprecierii durabilităţii acestora şi pentru asigurarea condiţiilor optime de aplicare a lucrărilor de întreţinere şi reparaţii necesare.

Informaţiile obţinute prin intermediul acestui sistem de monitorizare vor fi corelate cu informaţiile obţinute *in situ*, bazate pe observaţii vizuale în cadrul lucrărilor de supraveghere şi pot oferi, în timp real, un tablou complet şi precis al caracteristicilor structurale şi de funcţionalitate ale podurilor.

Sunt evidenţiate avantajele utilizării acestui sistem integrat de monitorizare, capabil să identifice în timp real procesele de degradare specifice acestor tipuri de structuri, să ofere un flux continuu, precis şi complet de informaţii, să permită reducerea costului lucrărilor de supraveghere cu 25%, optimizarea adoptării deciziilor de efectuare a lucrărilor de întreţinere şi reparaţii, şi, implicit, optimizarea alocării resurselor financiare necesare în procesul de management al podurilor.