Modeling of Environmental Effects on Bridge Components: Possibilities of Cellular Programming

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Abstract. The early deterioration of concrete structures due to the effects of external aggressive environment is well known. This paper presents cellular automata approach to the problem of lifetime assessment of concrete structures, particularly bridges, under the diffusive attack of external aggressive agents. The diffusion process is modeled by cellular automata technique as a 2D task describing more realistically the spatial variability of e.g. the chloride ingress within dynamic environment. The effectiveness of the proposed methodology arises from the transparent implementation yet complex behavior of two selected numerical case studies.

Keywords: diffusion process, concrete structures, service life, simulation, cellular automata, aggressive environment, bridges.

1 Introduction

Concrete is generally effective in protecting embedded steel from corrosion. This protective capability may be reduced significantly due to external stressors affecting the reliability of the structure during the course of time. Current standards require minimum concrete cover thickness, which calculation is, among others, based on the given level of environmental exposure. The amount of concrete used as a protective layer significantly affects the cost, reliability and service life of the structure. Such approach does not directly allow a design focused on a specific service life and/or a specific level of reliability – this would require the inherent uncertainties in relevant characteristics to be dealt with while assessing the service life of a structure. Such tasks necessarily require the utilization of stochastic approaches, analytical models of degradation effects and also simulation techniques, all based on the experimental evidence and relevant observations of structures under real conditions.

This work focuses on nontraditional numerical representation of selected processes, relevant to the assessment of environmental exposure, using cellular automata (CA) technique, a very simple yet effective method, to solve the diffusion equation according to a given set of boundary conditions within dynamic environment. In this way the initiation time (time to reinforcement corrosion onset) is assessed more effectively than by traditional 1D models.

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2 Spatial Simulation of Chloride Penetration Based on Cellular Automaton

2.1 Field of Application

A bridge construction during its life cycle undergoes a number of events of which few have indispensable effect on the structural health. Some of the most suitable phenomena for cellular automata simulation are presented in this section. Seasonal de-icing salt application may be considered in certain areas noting that the diffusion takes place inside the concrete structure also when there is no external chloride feed, e.g. in summer. During the event of rain the exposed surface regions may have their chloride concentration reduced due to the wash-out effect. Different diffusion components may also be considered, such as carbon dioxide or water. Another example could be the effect of UV rays or temperature. All of the mentioned above would have instant effect on the local material and diffusive properties of the structure. It is clear that such system would be relatively easy to create in terms of cellular programming but would require a large number of field data together with theoretical knowledge of individual phenomena and their interactions. Note that the presented case studies are based on the single-parameter cell system.

2.2 Diffusion Equation

The simplest model to describe the process of diffusion of chemical components is based on Fick´s law. For the case of single component diffusion in isotropic, homogeneous and time-invariant media it leads to the second order partial differential equation [1,2]:

$$\frac{\partial C}{\partial t} = D\nabla^2 C \tag{1}$$

where C is concentration of diffusion component (at particular point and in particular time) and D is diffusivity coefficient of the medium. The diffusivity coefficient for concrete depends on many parameters like relative humidity, temperature and others; generally it is time dependant.

The equation (1) can be effectively solved by using cellular automata; the solution was adopted from Biondini et al. [1,2] and further developed as briefly described in the following text.

2.3 Cellular Automata

The structure is for our purposes represented by a 2D grid of cells. Each cell has its state value representing the component concentration (e.g. the chloride ions). The process of chloride ingress is governed by a local rule in which the evolutionary coefficients Φ_i (i = 1,2,3,4,5) assign the level of chloride concentration redistribution within the cell's neighbourhood (von Neumann, radius 1):

$$X_{(t+1)} = \Phi_1 X_t + \Phi_2 N_t + \Phi_3 E_t + \Phi_4 S_t + \Phi_5 W_t \tag{2}$$

where the discrete variables $\{X_t, N_t, E_t, S_t, W_t\}$ represent the concentration of the component in the given cell at time t. The values of the evolutionary coefficients Φ_i must verify the following normality rule:

$$\sum \Phi_i = 1 \tag{3}$$

as required by the mass conservation law. Clearly, for isotropic media the symmetry condition $\Phi_2 = \Phi_3 = \Phi_4 = \Phi_5$ must be adopted in order to avoid the directionality effects. It can be proven that the values $\Phi_1 = 0.5$ and $\Phi_{2,3,4,5} = 0.125$ lead to a very good accuracy of the automaton. The relationship between the cell size Δx, time step Δt, diffusion coefficient D and chloride evolutionary coefficient Φ_1 (governing) is mandatory for the whole grid of cells within a time step:

$$D = \Phi_1 \Delta x^2 \Delta t^{-1} \tag{4}$$

Stochastic effects may be treated as well, modifying the procedure by assuming the evolutionary coefficients Φ_i to be random values with a given probability density function. Generator of pseudorandom numbers based on the ziggurat method was adopted [3]. One of the essential parts of the CA configuration is the boundary rule setting, or in other words the definition of the system's behaviour in the areas where a contact is with the outer medium, i.e. with a place beyond the simulation region. Several types of boundary rule have been implemented. The best rule suitable for the comparison with conventional 1D analytical models (for chloride ions penetration) is the mirror neighbour rule of hemisphere action, where the state values of the adjacent cells are governed according to the boundary region condition in such a way, that the sum of all state values within a defined cell's neighborhood (von Neumann, radius 1) is equal to the same sum in the successive time step. Note that this approach to the boundary problem is suitable only for the case, where it is supposed that the transported quantity does not leave the simulation region once it enters. This might be the case of chloride ions although it is known, that in reality there is some kind of back-propagation. It is an attractive topic to appropriately define the boundary system interaction for different transport phenomena; however for the purpose of this work it was rational to use some sense of simplification when dealing with the task of boundary interaction.

2.4 Local Degradation Modeling and Probabilistic Simulation

In the case of the comparison to the 1D model the aim is to configure such a CA that will provide similar results as the 1D material point model. To achieve this, it was useful to create such a configuration of CA, that the component concentration at certain point at certain time was affected only by the propagation from one direction without considering the gain/loss of the component from the other directions. This demand would satisfy an infinite large simulation area (cross section) or a special modification of the boundary rules, which would simulate the coverage of the infinite simulation area. The analytical 1D model for comparison was adopted from Papadakis using FREET-D tool [4]. The results were almost identical.

3 Case Studies

3.1 An Application to an Existing Bridge

The bridge was designed in 1969 as a highway crossover in South Tyrol. The inspections showed that there is a serious degradation of the piles and beams in the junctions of the prestressed V beams. These weak zones are mainly caused by an insufficient sealing of the pavement in the region of the expansion joints over the piles. As the bridge was demolished in spring 2008, concrete samples were possible to drill and chemical analysis was performed. Chloride concentrations were measured and localized (based on heuristic expert judgment). Due to the short time period before the paper finalizing, this data were not utilized as input concentration for CA approach to calibrate the present stage of analysis and to make realistic prognosis in time. Figure 1 shows the estimated initial distribution of de-icing salts concentrations (half of the bridge), the maximal surface chloride concentration being 0.2 % Cl- per cement content. Note that distribution of initial concentration along bottom part of the bridge was estimated from the location of stiffeners and supports (leakage through joints), where higher "localized" degradation was detected.

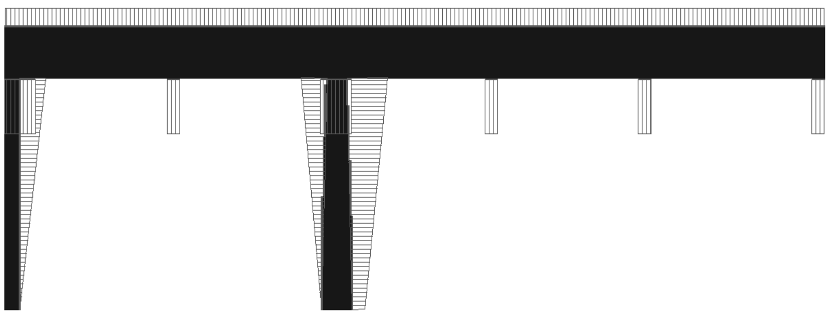

Fig. 1. Distribution of initial concentrations of aggressive agents as considered in 2D model

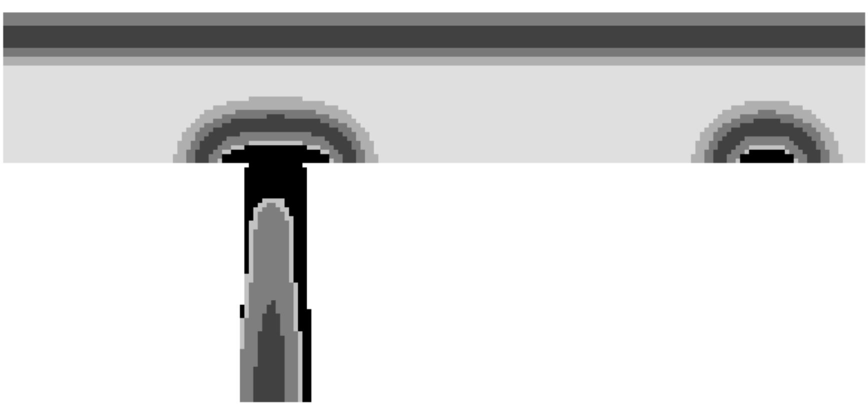

Fig. 2. Predictions of chloride concentrations development for 30 years – detail around the supporting pier with critical concentration region (black)

Prediction of chloride concentrations for 30 years is shown in Figure 2. The light tone represents the undamaged state of a cell, while the darker tone represents the degraded state. Black regions represent parts where chloride concentrations were greater than critical chloride concentrations (here 0.4 % Cl- per cement content). The utilization of such approach will enable the engineer to focus on modeling or prognosis of reinforcement corrosion in most jeopardized locations, namely to assess the initiation time, i.e. the durability limit state; and thus support the decision making.

3.2 Reinforcement Corrosion

In the presented example a reinforced concrete rectangular cross section is exposed to chloride ingress. To illustrate the versatility of CA four different cases are assumed that differ by the surface areas exposed to chloride action as illustrated in Fig. 3. Surfaces bounded with the dashed line were supplied by chlorides in the way that the surface concentration remained constant over the whole time period except for the case IV where the more realistic seasonal (winter) de-icing salt application was applied. Both reflecting and absorbing boundary conditions (BC) are suitable depending on expected behaviour. For example using the combination of absorbing BC and seasonal chloride feed an interesting task would be to find the equilibrium state when the chloride concentration in the structural core stabilizes on a certain level while the fluctuations remain in the peripheral regions, i.e. after certain time the same amount of chlorides from winter salt application is washed out in the summer having no effect on the total annual Cl^- increment.

Consequently the development of the chloride concentration in the vicinity of reinforcing bars is monitored to demonstrate various performances of different boundary conditions.

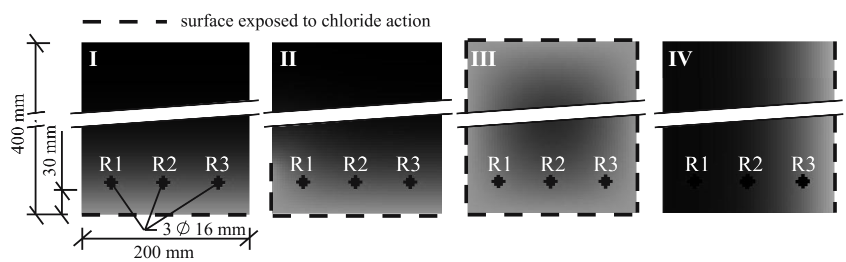

Fig. 3. Chloride ingress for different boundary conditions (I, II, III and IV) after 30 years of exposure. Higher concentration values are in light tone, lower are black. Steel reinforcements are R1, R2 and R3.

4 Conclusions

The paper exploits possibilities of cellular programming as transparent and general approach to applied degradation modeling of concrete bridges. The authors believe that the approach is promising, especially in the context of lifetime reliability assessment. The South Tyrol Bridge serves as testing application example of the first part of the approach generally applicable for any degrading concrete structure.

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