論文の内容の要旨

論文題目　**PROBABILITY BASED MAINTENANCE PLANNING FOR RC STRUCTURE DETERIORATED BY SALT ATTACK**

（塩害劣化を受ける **RC** 構造物の確率論的維持管理計画）

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Reinforced concrete (RC) structures are deteriorated with time when they are subjected to the aggressive environment. In order to maintain the safety and serviceability, most structures need the appropriate maintenance program to be applied during their service life. In 2002, Japan allocated approximately 13.5 trillion yen, which is 21.5% of the total construction budget, to the maintenance projects of the existent infrastructure. The ratio of maintenance budget to the overall construction budget is expected to continuously increase in the future because of increasing number of aging structures. In the near future, infrastructure maintenance will become the major task which has to be significantly concerned.

Corrosion of reinforcing steel due to salt attack is one of major mechanisms deteriorated RC structure around the world. Due to expansion of corrosion product of reinforcing steel, pressure is generated inside the concrete and covering concrete is under tensile stress. Corrosion crack, spalling, or failure of structure is the results of steel corrosion. In order to ensure safety and serviceability of deteriorated structure, maintenance planning program, which is related to inspect current structural condition, predict future structural condition, and decide necessary action to be performed, has to be conducted.

Currently, there are many standard specifications of maintenance program for RC structure proposed by various organizations as well as various researchers. Due to variations of structural properties as a reason of workmanship, material properties, or environmental conditions are normally observed in the reality. Therefore, most of current maintenance program uses deterministic model to predict future condition of structure and is normally specified safety factor to cover the variations of structural properties and ensure the safety of structure. This leads to over-design and high cost of structure than the actual requirement. Some researchers also proposed maintenance program with deterioration prediction model stochastically based on Markov process. The Markov process assumes that progress of deterioration only depends on the

current structural condition and neglects the improvement actions taken in the past. As well as, database of deterioration rate of similar structure and environmental conditions are required as an input in the prediction. So its application is limited to only the similar group and environment of structures. Therefore, in this study, a new probabilistic based deterioration prediction model is proposed. Benefits of both deterministic model of deterioration prediction and stochastic model of variation of structural properties in reality are combined in the method proposed in this study.

The main objective of this study is to propose a maintenance planning program based on optimization of life cycle cost that considers actual uncertainties of structural properties, and environmental conditions; considers deterioration mechanisms of structure both before and after being repaired. Variation of deterioration degree and probability of failure can be calculated. As a result, expected repairing cost and failure cost can be estimated. Finally, life cycle cost is determined and maintenance planning is decided based on the intervention that shows the minimum life cycle cost. However, scope of this study is still limited to RC structure deteriorated by salt attack as it is main mechanism rapidly deteriorated RC structure.

Firstly, deterioration prediction model for chloride induced steel corrosion of existing RC structure and repaired RC structure are proposed. Various effects such as crack width, macrocell corrosion, and performance of repairing system are considered to predict the future structural condition along the service life. Chloride diffusion along the crack width, macrocell corrosion due to non uniform chloride distribution, and corrosion crack width propagation are considered in the deterioration prediction model. Surface coating, patching repair, cathodic protection, and its combination are considered as options to repair deteriorated RC structures. For surface coating, durability against chloride penetration and cracking of surface coating are discussed. For patching repair, durability against chloride penetration as well as macrocell corrosion due to different in chloride concentration and material properties are considered. For cathodic protection, service life of cathodic protection is considered and corrosion can be neglected during the service life of cathodic protection.

Inspection program is recommended to determine actual variation of structural performance and environmental conditions. Parameters to be inspected are recommended based on result of sensitivity analysis. The minimum number of sample to be inspected are recommended based on required level of confidence, acceptable level of error, and ratio of target portion to the whole structures. Goodness of fit test is used to determine the most suitable probability density function in order to define the inspection result and use in the calculation.

Monte Carlo simulation is selected to solve the reliability problem. Probabilities of failure of structure due to chloride induced corrosion are determined. Limit states that are considered

include corrosion initiation, corrosion crack width, and concrete spalling. Inspection results of actual structure are considered to be utilized as an actual variation of structural properties in the determination of probability of failure. Number of evaluation times of Monte Carlo simulation is tested in order to produce reliable and reproducible result. Probability of failure and variation of deterioration degree can be determined annually.

Life cycle cost is used to decide the most suitable maintenance planning. In this study, repairing cost and failure cost are considered as life cycle cost. Repairing is conducted when corrosion crack width reach the limited value. Repairing cost is composed of fixed repairing cost, variable repairing cost, and annual repairing cost. Fixed repairing cost is assumed to be fixed at every time of repairing. Variable repairing cost is assumed to vary with the predicted variation of deterioration degree. Annual repairing cost is also considered in case of cathodic protection that is required the maintenance of the system and electric power. History price of repairing cost is used in the calculation. Failure cost is composed of user cost and cost of death. User cost is calculated from time value and user loss time that relating to variation of deterioration degree. Cost of death is included economic loss of death of a person. Total repairing cost and failure cost are determined throughout the service life of structure with also considering the effect of discount rate. Maintenance methods, schedule of maintenance, cost, and discount rate are considered to affect the result of maintenance planning. The schedule of repairing, method of repairing, expected repairing cost can be obtained from the result of this study. Both of maintenance planning and budget allocation can be achieved by using the method proposed in this study.

Finally, examples of application of method proposed in this study to decide maintenance program for the actual RC structures are given. Actual inspection program is conducted and obtained results are used in the prediction. The lowest life cycle cost of scheduled and method of repairing can be decided for each case studies. Different of life cycle cost between different repairing method, and different durability of structure are shown in the result.

However, result of optimization of maintenance program largely depends on repairing and failure cost. There is also a difficulty to obtain an update and reliable cost data. So it is strongly recommended that database about repairing and failure cost relating to deteriorated structure should be focused. In order to determine actual variation of structural properties, the suitable inspection methods have to be considered. However, there is still difficulty to inspect resistance of concrete against penetration of aggressive ion. Develop of inspection method to be reliable inspect this property with affordable resources should be considered. Corrosion of reinforcing steel is actually time-dependent mechanisms. Due to formation of rust, changing in temperature or resistance of concrete, corrosion current can be affected. In the future, these factors should be

considered in the prediction model. Moreover, there are many repairing methods newly developed repeatedly. Long term durability of those repairing methods should be carefully confirmed as many repairing methods found to accelerate deterioration of structure after being repaired. Spalling is one of failure that can cause severe damage to users and its prediction model for spalling of covering concrete has not been well developed yet. Deterministic model to predict spalling should be developed in the future. Effects of macrocell corrosion on corrosion crack width are significant. However, in this study only the different in material properties and chloride concentration are considered. There are other factors such as distance between cathodic and anodic area, time dependent properties of macrocell, etc. should also be considered in the future. Finally, not only salt attack that significantly deteriorates RC structure, but also other mechanisms such as carbonation, freezing and thawing, or loading should also be considered. Maintenance planning program for those deterioration mechanisms should also be proposed. In the final, integration of all mechanisms into one maintenance planning program is the final intention.