Development of a Flow Rate Equation for Predicting Leakage through Concrete Cracks

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1. Introduction

The containment building of a nuclear power plant plays an important role in preventing the leakage of radioactive material into the environment. Therefore, predicting the amount of leakage through the containment building is essential for safety analysis. However, through-wall cracks can occur in containment buildings under various conditions such as earthquakes or extreme internal pressure. In this study, we aim to predict the amount of fluid leakage through concrete cracks. The results can be used to develop an environmental leakage assessment model based on the containment building cracks. This model is expected to be used to evaluate the risk of radioactive material leakage in the event of a severe accident.

2. Methods and Results

A flow rate equation considering the concrete crack roughness was derived, and the results were compared with fluid simulation results using ANSYS Fluent.

2.1 Leakage through Concrete Crack

Numerous studies on leakage through concrete cracks have been conducted since the 1970s [1, 2]. Along with this, research has been carried out on the development of flow rate equations to predict leakage amounts. In Ref. [3], crack geometry properties such as crack width and length were used to calculate the flow rate, and a theoretical flow rate equation for a single crack based on 2D Poiseuille's flow was derived. For turbulence flow, the Darcy-Weisbach equation is used. This equation has been updated based on numerous research findings, and detailed information can be found in Ref. [4]. The friction factor f for fluid friction was first proposed by Blasius as a function of Reynolds number. The flow rate equation proposed in Ref. [3], Darcy-Weisbach pressure loss equation, and Blasius formula are:

$$(1)\ Q = BW^3\Delta P/(12\mu t)$$
$$(2)\ \Delta P = f \cdot \rho t v^2/(2D_H)$$
$$(3)\ f = 0.3164/Re^{1/4}$$

where Q is the flow rate, B is the crack length, W is the crack width, ΔP is the pressure difference, μ is the viscosity, t is the crack thickness, v is the mean flow velocity, D_H is the hydraulic diameter and Re is the Reynolds number. Based on Equations (2) and (3), a flow rate equation for the turbulent flow of fluid through concrete cracks was derived.

2.2 Fluid Simulation

To validate the flow rate equation, fluid simulations were conducted using concrete crack surfaces, and the results were compared. The concrete specimen shown in Fig. 1 was fractured using a three-point bending test, and its cross-section was then scanned using a 3D scanner. The process of obtaining the crack surface is shown in Fig. 2. A mesh for fluid simulation was generated based on the scanned data. Simulations were performed with 15 crack surfaces, and the input parameters are presented in Table I. The crack geometry parameters are presented as the mean values of the 15 surfaces in Table I. Here, α represents the calibration parameter for the turbulent flow between the theoretical and simulation results.

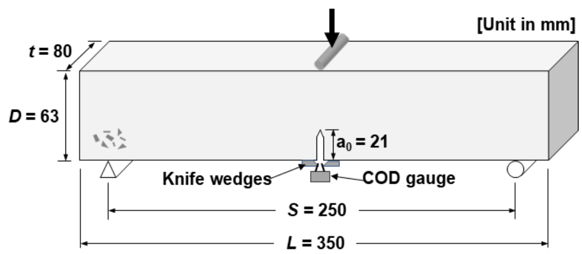

Fig. 1. Details of concrete specimen.

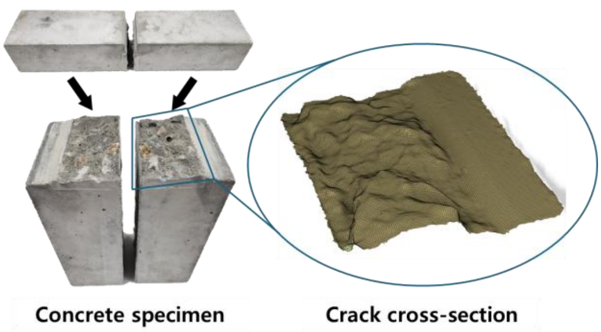

Fig. 2. Schematic of the crack surface obtaining process.

Table I: Input Parameters.

Parameters	Value
B	6.75 cm
t	4 cm

W	0.15 mm
Re	16,609
ΔP	101,325 Pa
ρ	1.22 kg/m^3
α	30.5

2.3 Flow Rate Equation

Considering crack roughness in the flow rate equation, the parameter R, which represents the maximum height difference of the crack surface as shown in Fig. 3, was added to the equation. The proposed flow rate equations, considering crack roughness, are presented in Equations (4) and (5):

$$(4)\ Q_a = 2.48Re^{1/8}\alpha WB\sqrt{\frac{\Delta PW}{t\rho}}$$

$$(5)\ Q_a = 2.48Re^{1/8}\alpha WB\sqrt{\frac{\Delta PW}{t\rho}}\left[\beta_1\left(\frac{W}{R}\right)^{\beta_2}\right]$$

The difference between two equations are dimensionless parameters for crack roughness. β_1 and β_2 were derived by curve fitting the simulation results, and the flow rates calculated using the two equations were compared with the simulation results. When crack roughness is considered, as in Equation (5), the error rate between the simulation results and the predicted by the equation decreases significantly to within 33%. The simulation results Q_s and the analytical flow rate by the equation Q_a are shown in Fig. 4. The coefficient of determination is 0.31, indicating that more data is needed to improve the model's accuracy.

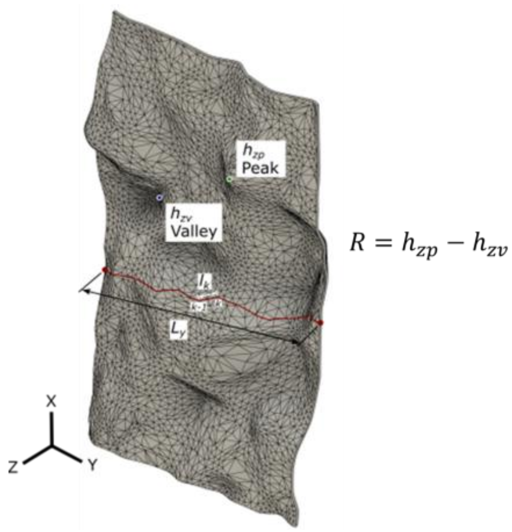

Fig. 3. Crack roughness (Note: In this study, crack roughness is defined as the maximum height difference of the crack surface).

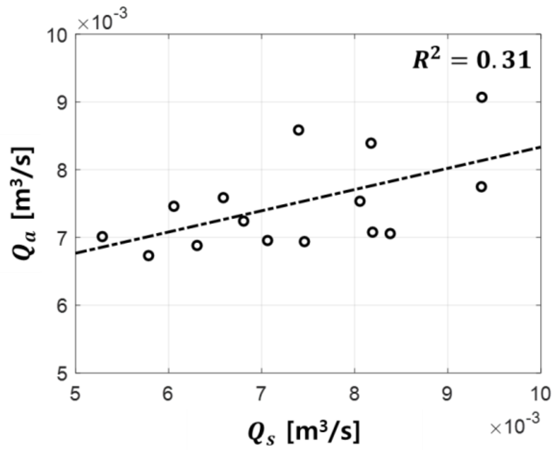

Fig. 4. Comparison of simulation and predicted flow rate.

3. Conclusions

This study proposes a flow rate equation to predict leakage through concrete cracks and validates it by comparing the flow rates obtained from simulations using actual concrete crack cross-sections with those predicted by the proposed equation. It was confirmed that considering crack roughness in turbulent flow results in more accurate flow rate predictions. Updating the flow rate equation with a larger number of specimens is expected to improve the model's accuracy. Additional sensitivity analysis will enable the evaluation of the impact of each parameter on the flow rate through concrete cracks. It is expected that future research will develop a flow rate equation capable of predicting leakage for various crack geometries and apply it to environmental leakage assessment in nuclear power plant containment buildings.

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