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Flow Rate Prediction for Concrete Cracks Incorporating Surface Roughness

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1. Introduction

Predicting flow rates through concrete cracks is essential for safety assessments of nuclear power plant containment buildings, which are designed to prevent the release of radioactive materials into the environment. Through-cracks in containment buildings can lead to leakage, and the resulting flow rates are influenced by crack geometry. In this study, a flow rate prediction equation was developed and updated based on numerical simulations using actual concrete crack surfaces. The proposed equation considers crack surface roughness to improve leakage prediction accuracy. This framework is expected to enable quantitative evaluation of leakage through cracks in containment buildings under severe accident conditions.

2. Methods and Results

Flow rates predicted by the proposed equation were compared with numerical simulation results obtained using ANSYS Fluent. Further details are provided below.

2.1 Modification of Surface Roughness Parameter

A flow rate equation was developed based on the Darcy-Weisbach equation [1]. Although the original equation was derived from a parallel-plate flow model, a roughness parameter was required to accurately predict leakage through concrete cracks. In a previous study by the authors, a flow rate equation considering a roughness of crack surface was proposed as

$$(1)\ Q_a = 3.56 {R_e}^{1/8} W B \sqrt{\frac{\Delta P W}{t \rho}} \left[\beta_1 \left(\frac{W}{R_c} \right)^{\beta_2} \right],$$

where R_e is the Reynolds number, W is the crack width, B is the crack thickness, ΔP is the pressure difference, t is the crack length, ρ is the fluid density, R_c is the crack surface roughness. The bracketed terms accounts for the effect of R_c and is dimensionless. The coefficients β_1 and β_2 were obtained from curve fitting of simulation results.

Various approaches have been proposed to characterize surface roughness [2]. In the preliminary study, R_c was defined as the maximum height difference of the crack surface. For simulations, actual crack surfaces were scanned to generate meshes, while geometric parameters, such as $W, B,$ and $t,$ were kept constant across all specimens. Air was used as the fluid, and ten specimens based on in-plane crack surfaces were analyzed. However, because these specimens exhibited a limited range of maximum height differences, the proposed equation failed to accurately predict flow rates as shown in Fig. 1a.

To address this issue, R_c was redefined following Ref. [3], which evaluated local surface roughness. This method was applicable to cracks with complex geometries and avoided difficulties related with mesh generation. Using the revised roughness definition, the coefficient of determination (R^2) between predicted and simulated flow rates increased to approximately 0.79, showing a significant improvement compared with the previous roughness parameter (Fig. 1b). Accordingly, the revised roughness parameter was adopted for subsequent simulations.

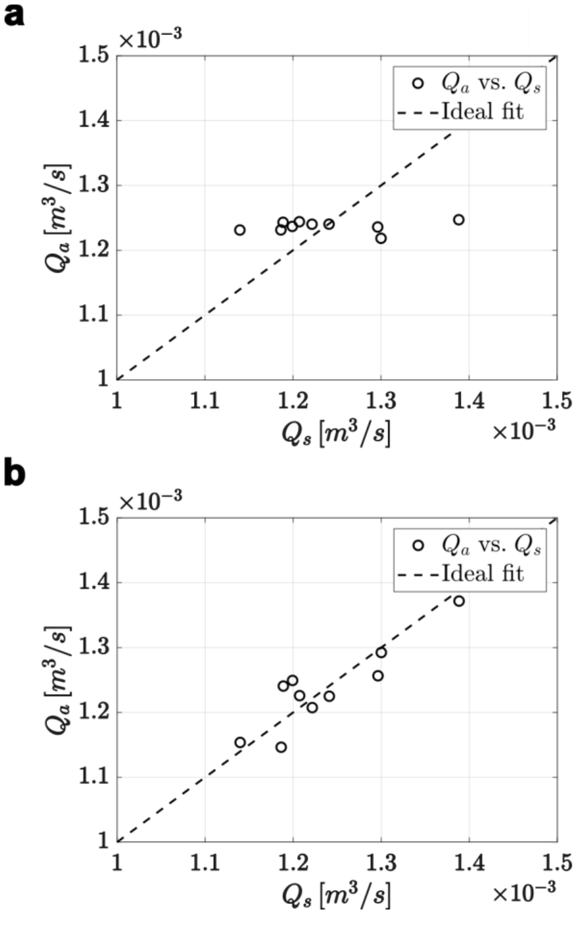

Fig. 1. Comparison of simulated (Q_s) and predicted (Q_a) flow

rates using different roughness parameters. (a) Roughness defined by the maximum height difference, (b) Roughness defined following Ref. [3].

2.2 Effect of Crack Width

Crack geometry strongly affects flow rates. To investigate the influence of the crack width, W values were measured from through-cracked concrete specimens. Histogram-based crack measurements were performed following Ref. [4]. A total of 18 crack surfaces, including both in-plane and out-of-plane cracks, were scanned and used for numerical simulations.

The results are shown in Fig. 2. R^2 reached approximately 0.99, indicating that the proposed equation accurately predicted flow rates across varying crack widths. However, the fitted coefficient β_2 was relatively small, approximately 0.04, representing that the effect of surface roughness became negligible when considering crack width.

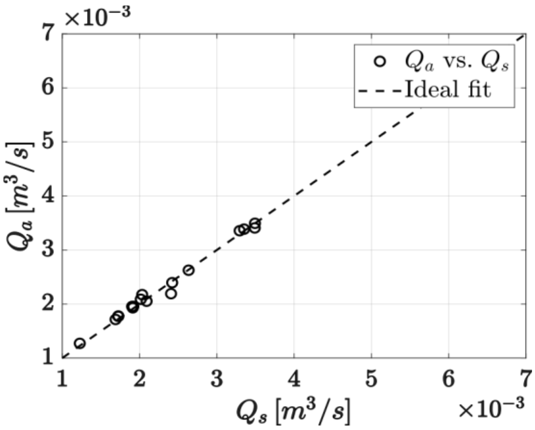

Fig. 2. Comparison of simulated (Q_s) and predicted (Q_a) flow rates for different crack widths.

2.3 Flow Rate Equation

As discussed in the previous section, crack geometry significantly affects flow rates. To investigate the influence of surface roughness, the meshes were regenerated using a consistent mean crack width of 0.15 mm for all 18 specimens. In addition, to better reflect the actual crack geometry, the average inlet and outlet surface areas were used in place of WB when predicting the flow rates in Equation (1).

When volumetric flow rate was used directly, prediction accuracy was significantly reduced ($R^2 = 0.19$). This reduction was due to variations in effective flow area among specimens. To address this issue, the volumetric flow rate of each specimen was divided by its average inlet and outlet surface area to obtain the flow rate per unit area, which is physically equivalent to the velocity, defined as

$$(2)\ q_a = 3.56{R_e}^{1/8}\sqrt{\frac{\Delta P W}{t\rho}}\left[\beta_1\left(\frac{W}{R_c}\right)^{\beta_2}\right].$$

The corresponding results are shown in Fig. 3. A relatively higher correlation ($R^2 = 0.53$) was observed, indicating that the equation based on flow rate per unit area improved agreement between the predicted and simulated results.

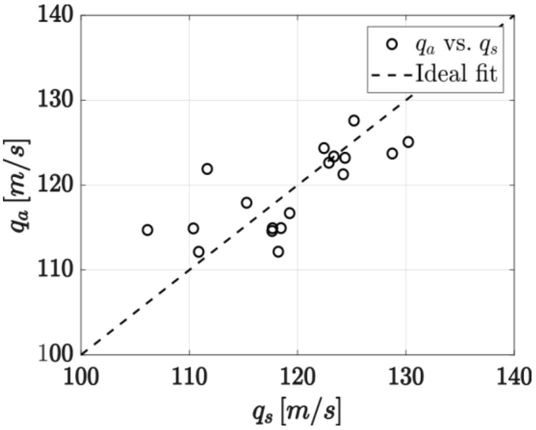

Fig. 3. Comparison of simulated (q_s) and predicted (q_a) flow rates per unit area.

3. Conclusions

This study updated a flow rate equation to evaluate leakage through concrete cracks. To better represent the crack surface characteristics, roughness and geometric parameters were modified. In addition, volumetric flow rates were divided by the average surface area to obtain flow rates per unit area, resulting in improved agreement between predicted and simulated values. The accuracy of the proposed framework can be further enhanced by incorporating larger datasets. Additional crack geometry parameters, such as crack tortuosity, will be considered in future work. It is expected that this approach can be utilized for safety assessment of nuclear power plant containment buildings.

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