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論文題目	Characterizing hydraulic properties of fractured rocks using DFN model and FEMDEM method for tunnelling applications（DFN モデルと FEMDEM 法を用いた亀裂性岩盤の水理的性質の特徴抽出とトンネル掘削への応用)		

（論文内容の要旨）

Fractures (e.g., faults and joints) provide pathways for fluid flow as hydraulic conductors or barriers that prevent flow across them. Characterization and detection of fractures in fractured rock mass have been of great interest in geotechnical, geological, geophysical, and hydraulic engineering practices. In particular, the relations between fractures and their physical properties (e.g., permeability, electrical resistivity, and seismic velocity) are fundamental to understanding fractured rock mass in tunnelling. Among several methods, the discrete fracture network (DFN) modeling approach has high capability of characterizing natural rock fractures. For stress-induced fractures (e.g., induced fractures around tunnel excavation), the hybrid finite-discrete element method (FEMDEM) is effective to model fracture initialization and propagation in rock mass. In this thesis, several methods were proposed to characterize fracture patters and their rock physical properties quantitively by the following six chapters.

Chapter 1 provides background information of fractures and their fractured rock physical properties (e.g., permeability, electrical resistivity, and seismic velocity). Also, DFN modeling approach as well as FEMDEM which characterize fractures in the rock mass are introduced briefly.

Chapter 2 presents a method for estimating effective permeability of fractured rock mass by using discrete fracture networks constrained by electrical resistivity data. Although the permeability of fractured rock mass is a fundamentally important property for the safe construction of civil and mining engineering structures such as tunnels, in-situ characterization of the permeability without resorting to hydraulic tests is difficult. For a quick estimate over a wide area, a method at a field-scale using geological and geophysical investigation data is proposed. The method is not based on the results of conventional hydraulic tests. Instead, it combines the stochastic generation of fracture networks with the crack tensor theory. The most important parameter for this method is the fracture length distribution. Although the distribution parameters in the DFN model are assigned through sampling, a bias is in general experienced, because of the limited sampling area. To improve the estimation of such parameter, in-situ electrical resistivity data and a symmetric self-consistent method are used as a constraint of the fracture length distribution. The proposed method is applied to the fractured crystalline rock mass of the Mizunami Underground Research Laboratory (URL) in the Tono area of central Japan. Its effectiveness and correctness are demonstrated by two case studies through good correspondence of the derived permeability with the in-situ measured permeability. For Case 1, an optimal DFN model with scaling exponent $a = 3.0$ was obtained with an in-situ measured resistivity of 2000 Ω·m. The corresponding average effective permeability is $\bar{k} = 5.30 \times 10^{-16}$ m^2, which is about half of in-situ measured permeability 1.0×10^{-15} m^2. For Case 2, the calculated $\bar{k}$ was 1.18×10^{-14} m^2, which was about four times greater than the in-situ measured permeability of 2.67×10^{-15} m^2. Based on the results of these two case studies, we conclude that the constrained DFN modeling approach using in-situ resistivity data can avoid constructing unrealistic DFN models with too many short fractures.

Chapter 3 presents a conceptual model to interpret both increases in seismic velocity and electrical resistivity after a tunnel excavation in fractured rock mass. Excavation of a tunnel results in the formation of an excavation damaged zone (EDZ) in surrounding rock mass. Generally, seismic wave velocity and electrical resistivity decrease after a tunnel excavation, because fractures initiate and propagate in EDZ. However, a special phenomenon where seismic velocity and electrical resistivity increased after tunnel excavation in the Horonobe Underground Research Laboratory (URL) was observed. A possible conceptual model for the phenomenon is proposed in this chapter. The conceptual model assumes that a decrease in liquid saturation around tunnel excavation induces the increases in seismic velocity and electrical resistivity in EDZ. The main cause of liquid saturation change originates from relative humidity variation in the tunnel. In addition, liquid saturation does not have a great influence on stress redistribution after excavation based on a hydro-mechanical modeling of excavation in a fractured rock mass using FLAC3D and TOUGH2. The rock gas saturations around the tunnel excavation surfaces increased after the tunnel excavation with decreasing in their increase rates. The electrical resistivities and seismic velocities in the rock mass were also increased. The numerical simulation incorporating our proposed model succeeds in explaining the phenomenon observed in the Horonobe URL.

Chapter 4 presents a model that links a unified pipe network method and FEMDEM fracture model for estimating equivalent permeability of fractured rock mass. Based on fractures in a fractured rock mass captured by a FEMDEM fracture model, a unified pipe network model that includes matrix pipes and fracture pipes is used to estimate equivalent permeability. Four representative cases studies were carried out to validate its applicability in calculating equivalent permeability. In Case 1 where a single fracture was embedded in a rock, k_{xx} decreased whereas k_{yy} increased as the fracture orientation increased from 0° to 90°, where the x and y axes are in the horizonal and vertical directions, respectively, and the angle is defined counterclockwisely from the x axis. In Case 2 where DFN models with different fracture densities were prepared, their equivalent permeabilities increased with increasing the fracture density in general. In Case 3 for a uniaxial compression test of rock specimen, both k_{xx} and k_{yy} increased with increasing the time step. Case 4 for simulating a deep tunnel excavation, permeabilities in different locations around the tunnel also increased generally.

Chapter 5 presents a numerical method that calculates equivalent electrical resistivity of fractured rock mass using an approach, similar to that of Chapter 4. The fracture initiation and propagation in intact rock mas is modeled by FEMDEM model, and the electric potential through fractures is simulated by an adapted unified pipe network model. To validate our novel proposed model, four representative cases studies were carried out. The first case was to estimate equivalent resistivities of intact rock mass in which a single fracture was embedded. The change in resistivity was revealed with the change in fracture orientation, and its change pattern was different with the direction. In Case 2, resistivities of DFN models decreased as fracture densities increased. Another case presented a laboratory test for uniaxial compressive strength (UCS) with estimating resistivities of a rock specimen. The resistivities decreased with increasing the time step. The last case clarified resistivity changes at different locations around the tunnel excavation, and the resistivities increased common to all the locations with increasing the time step.

Chapter 6 summarizes the main results obtained by this dissertation and describes future, essential works.